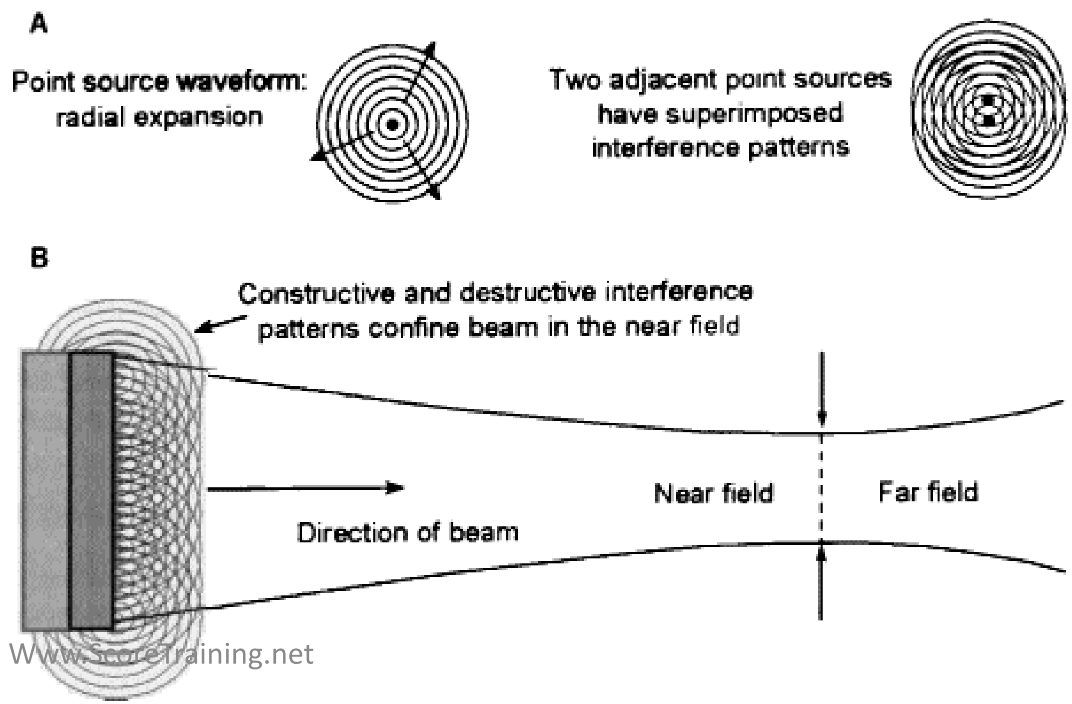
Beam geometry

1- Unfocussed beams

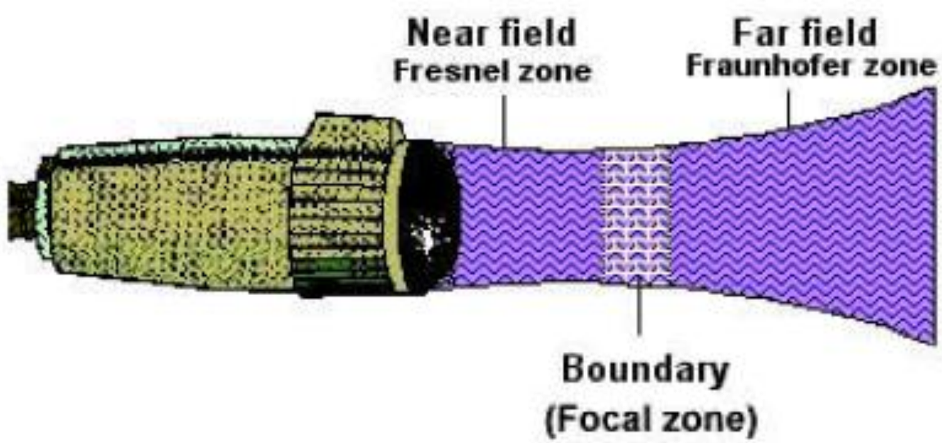
Probe diameter and beam shape:

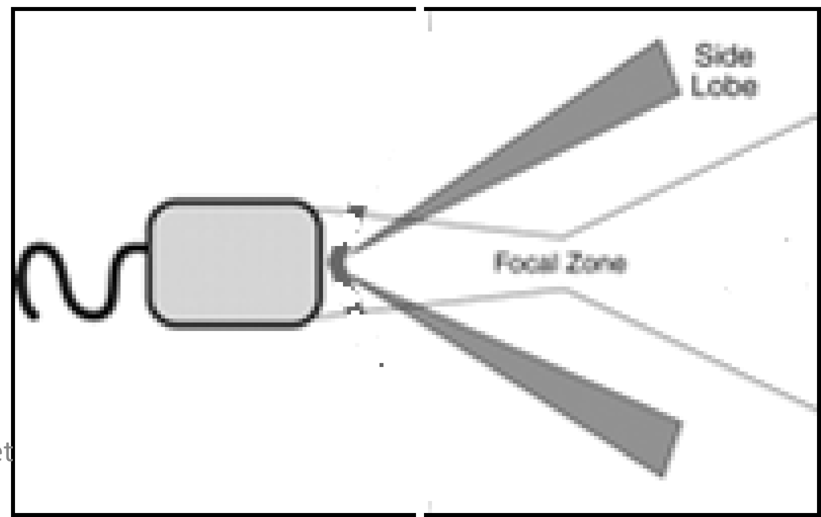
- If transducer has diameter ≤ λ (≈0.5mm) → sound would spread out equally in all directions
- If probe has diameter D (e.g. 10 λ) → sound is projected forwards , with the beam diameter ≈ D (HUYGEN'S principle)
- Explanation:
  - Waves are in phase (with constructive interference) in the forward direction
  - Waves are out of phase (with destructive interference) in any other direction



Zones of unfocused beams

- **Near (frensel) zone:**
  - The portion of the beam close to the face of the transducer has a width ≈ crystal width
  - Width of the field changes little in it
- **Far (fraunhofer) zone**: zone in which the field diverge (interference effect is lost)
- **Focal region:** junction of the two zones
- **Side lobes:** small low intensity beams outside the main beam , due to vibration of the edge of the disc (cause artifacts)



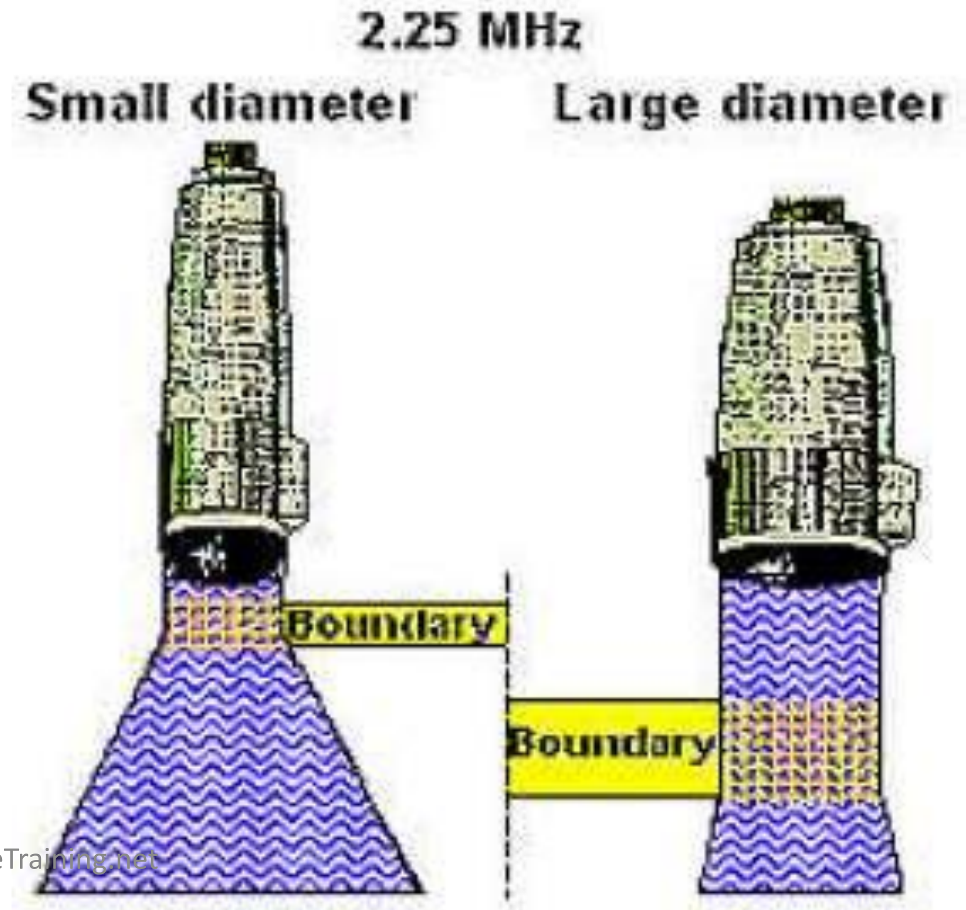


Factors affecting location of focal region

1) crystal diameter (D):

near zone length α D^2

Far zone Angle of divergence α 1/D

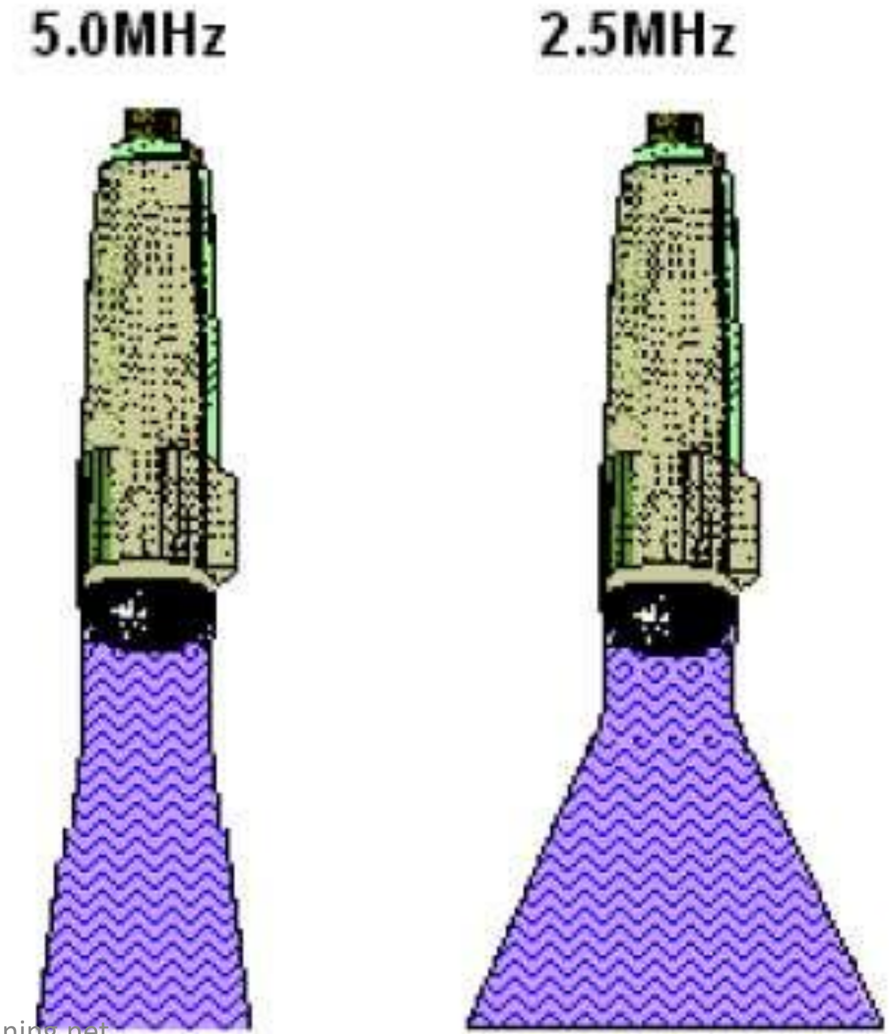


2) ultrasound frequency :

near zone length α F

Angle of divergence α 1/F

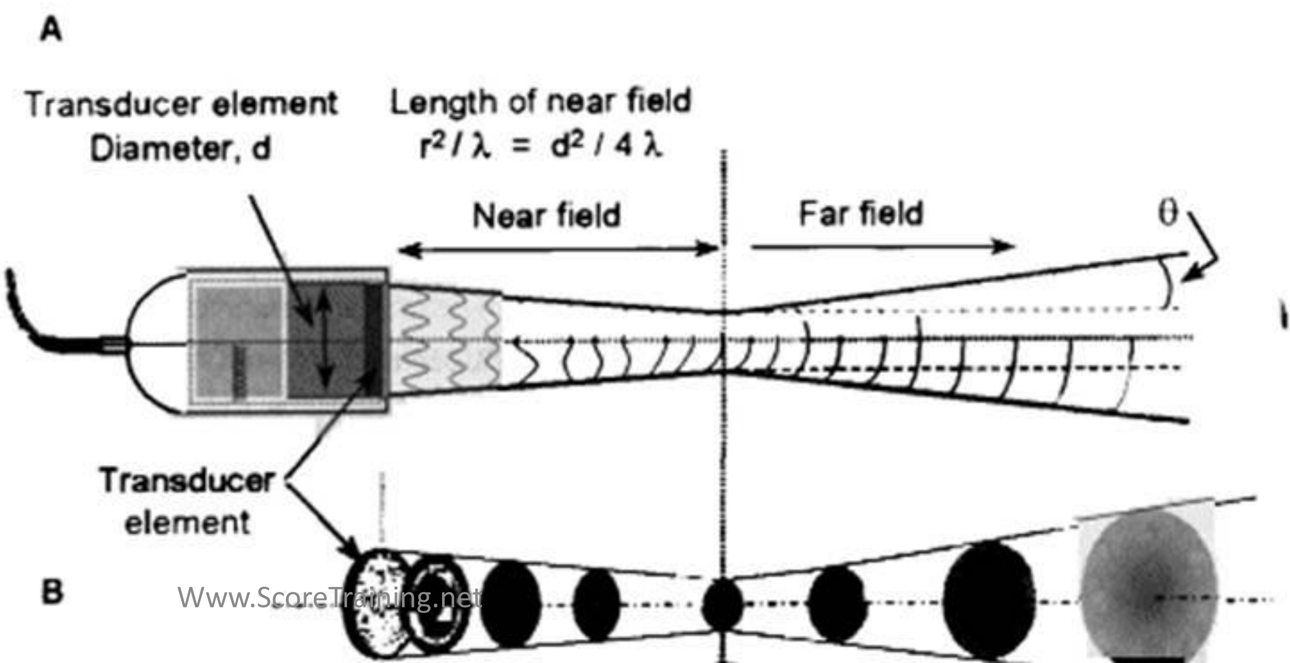
i.e. ↑F→ (more collimated beam)



Equation:

$$NZL = \frac{D^2}{4\lambda}$$

NZL= near zone length
D= crystal diameter
λ = ultrasound wavelength



Focused beams

Goal of focusing: focusing the beam at a particular depth corresponding to region of diagnostic interest will cause:

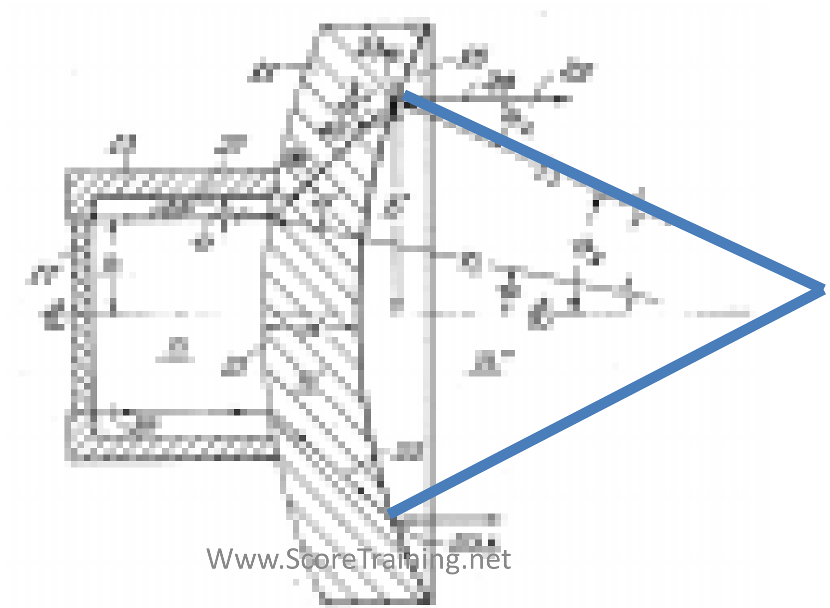
- Improvement in lateral resolution
- Concentration of intensity to that region , so that producing strongest echoes

Methods of focusing:

1- using concave piezoelectric element: the greater the curvature , the shorter the focal lens

2- mechanical focusing : see later

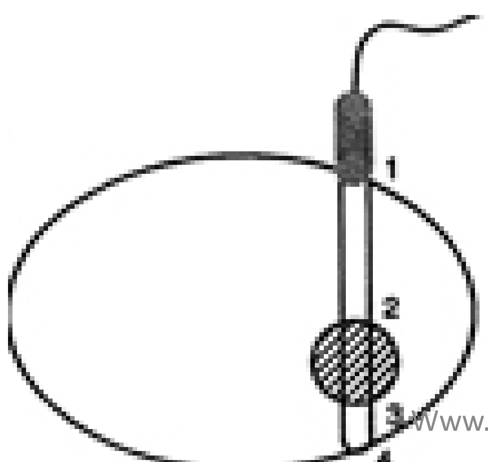
3- electronic focusing: see later

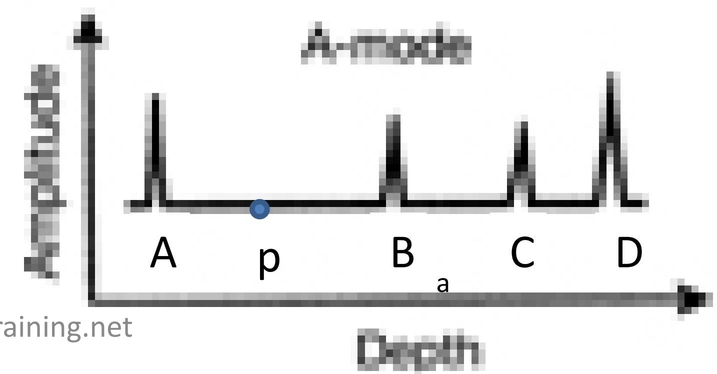


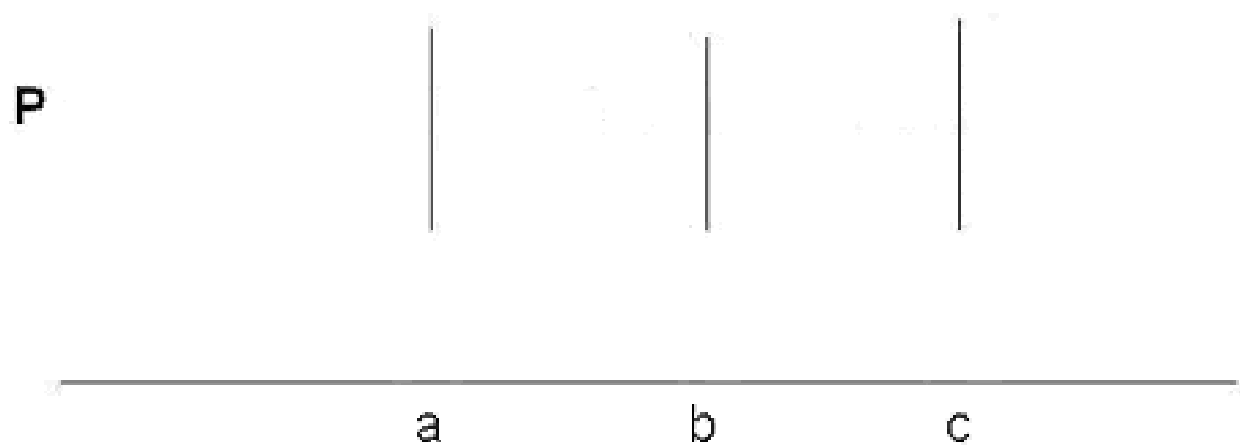
Ultrasound modes

A-Mode (amplitude mode)

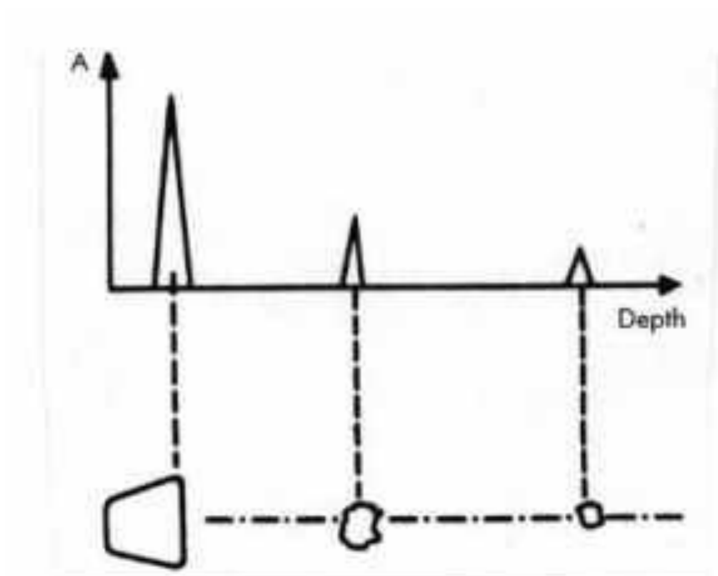
- Idea: simply show positions of tissues interfaces
- Process:
  - When probe is pulsed , 2 simultaneous processes occur:
    - Ultrasound pulse travel in the patient by certain velocity
    - Light spot start to move from the left edge of the display screen at a constant speed
  - U/S pulse reach interface (**2**) at time t (at the same time light spot is at point **p**)
  - Echo pulse take another time t to return to probe (light spot at point B)
  - A short vertical blip is produced at point B in response to the received echo (its height α echo strength)
  - Other interfaces (3&4) produce blips at C & D respectively
  - Position of the blip indicates the depth of the corresponding interface (a ruler is used to superimpose on the horizontal trace)






P
a
b
c

- Uses: eye examination , identifying breast cyst and brain midline displacement
- To provide sustained image:
  - Pulse repetition frequency of 1KHz is used (pulse duration = 1 ms)
  - Transducer is in transmit mode for 1 µs , and in listening mode for 999µs

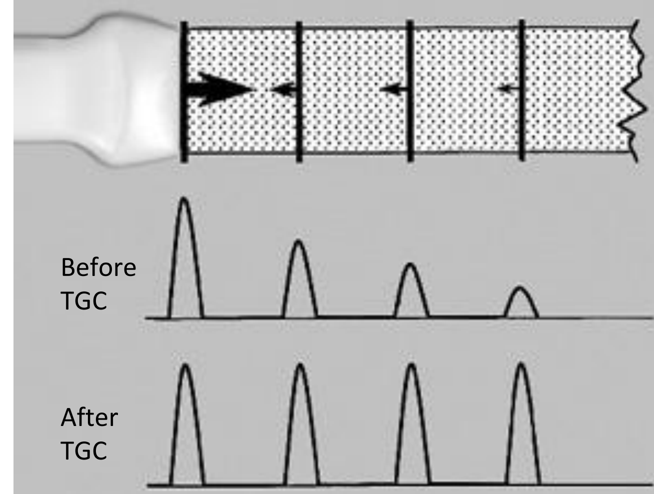


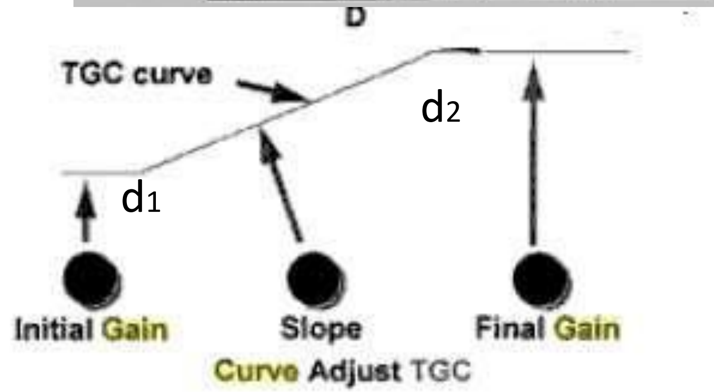
Problem: deeper interfaces in the body produce weaker echo than identical interface near the surface

Explanation: Amplitude of sound pulses decrease as it travel in tissues (due to attenuation) , and echo pulse is also attenuated

Solution: Time gain compensation (TGC):

- A sound amplifier (+ve dB gain) automatically increasing echo intensity in proportion to time elapsed (distance traveled)
- TGC is varied typically from 0 – 50 dB
- Gain is not applied until the region of interest is reached at threshold depth (d_1) , then increased linearly until depth (d_2)
- Threshold and slope of TGC can be changed manually



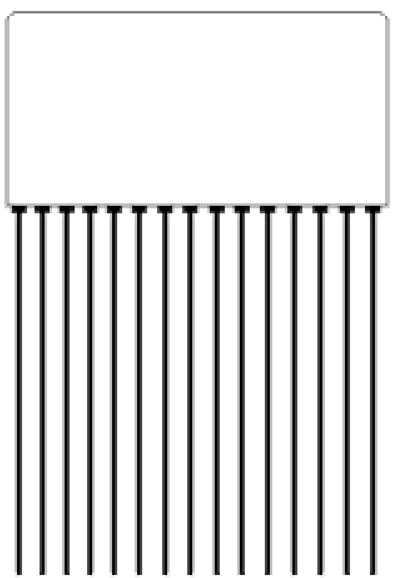


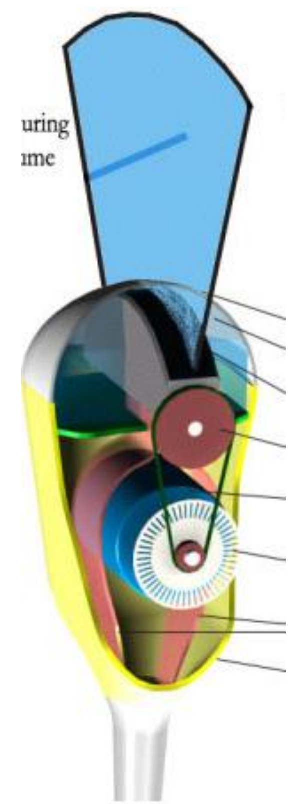
B-Mode (brightness mode)

1) A slice of the patient is imaged

- **Method:**
  - U/S pencil beam (scan line) scans back and forth across 2D section of the patient
  - Complete sweep (complete set of scan lines) = one displayed frame

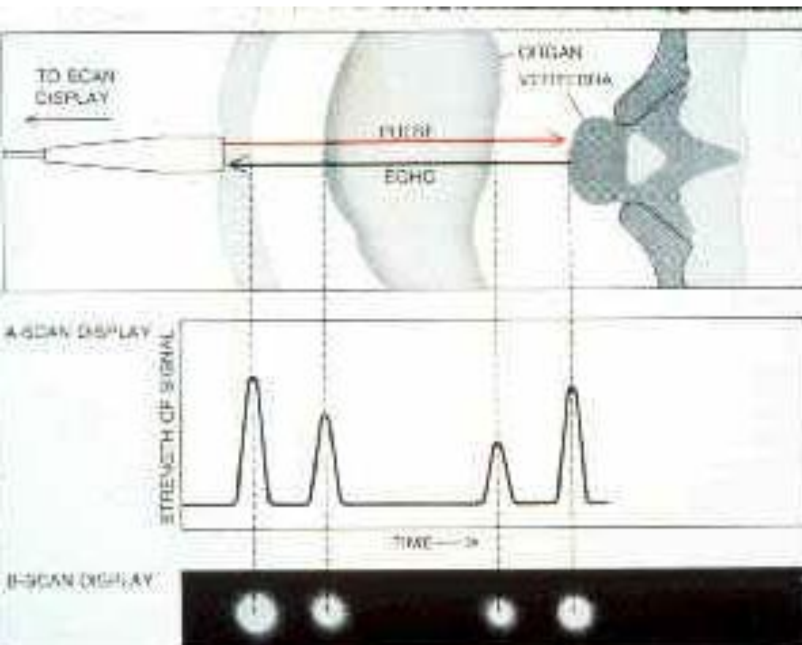
compare to A mode

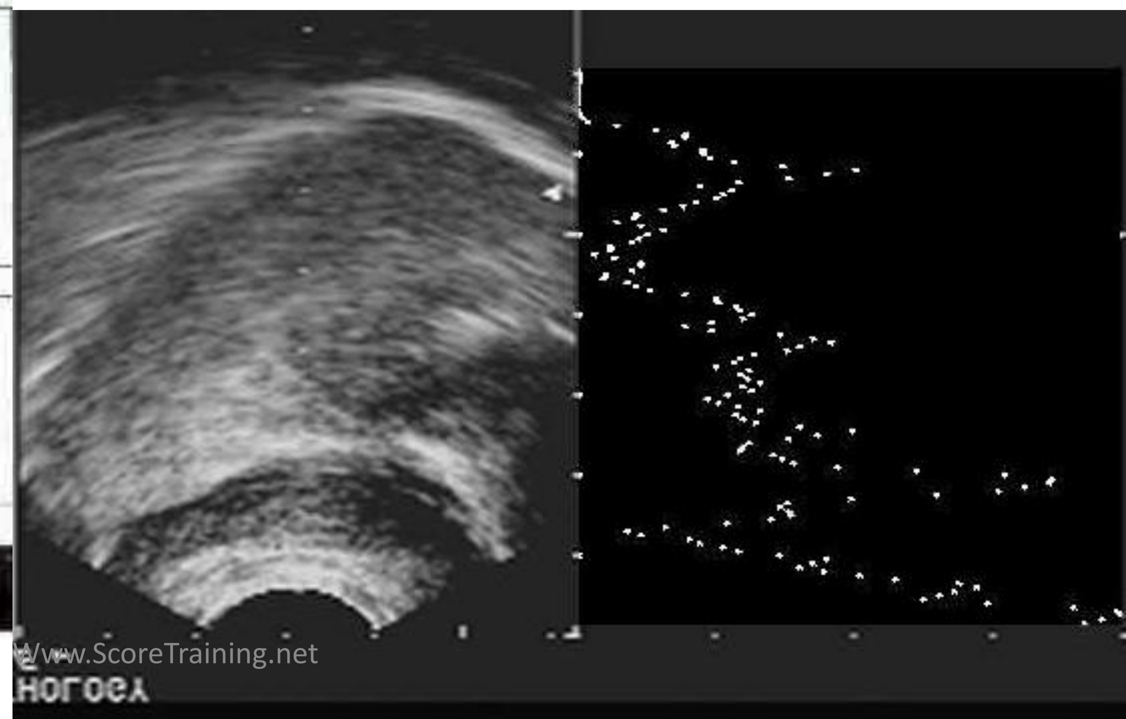




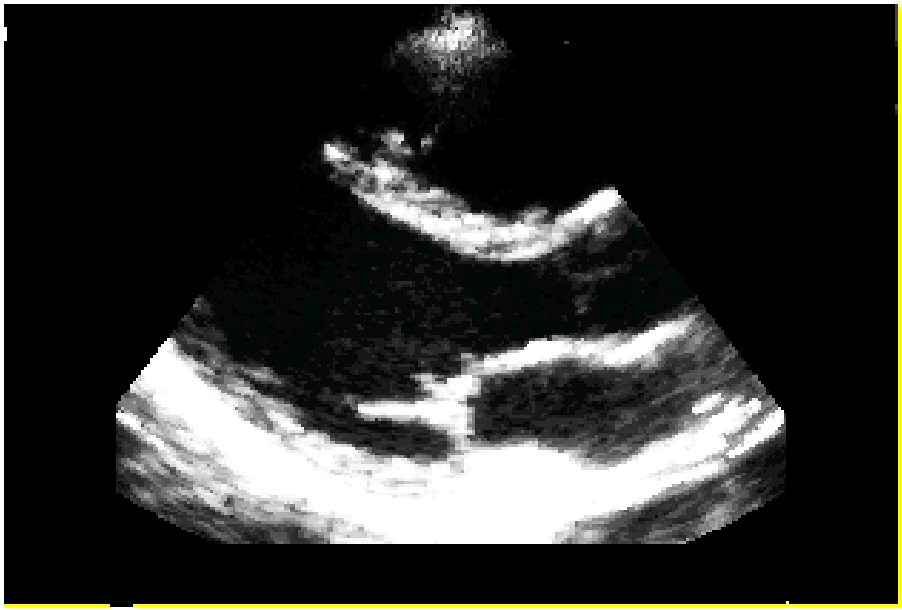
2-echoes from interfaces at each scan lines will be displayed Just like A-mode, but:

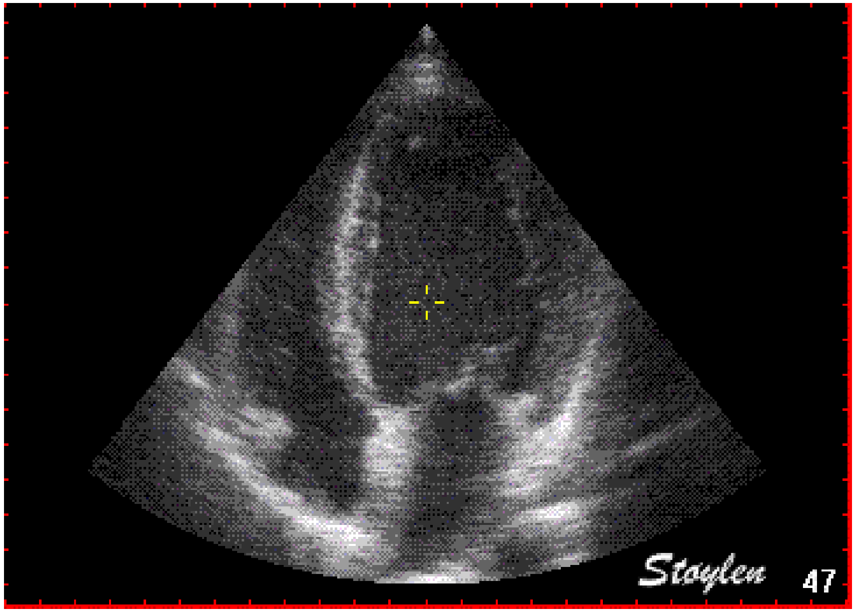
- Seen as bright dots (not blip)
- brightness α echo strength
- Trace itself will be suppressed
- TGC is also used



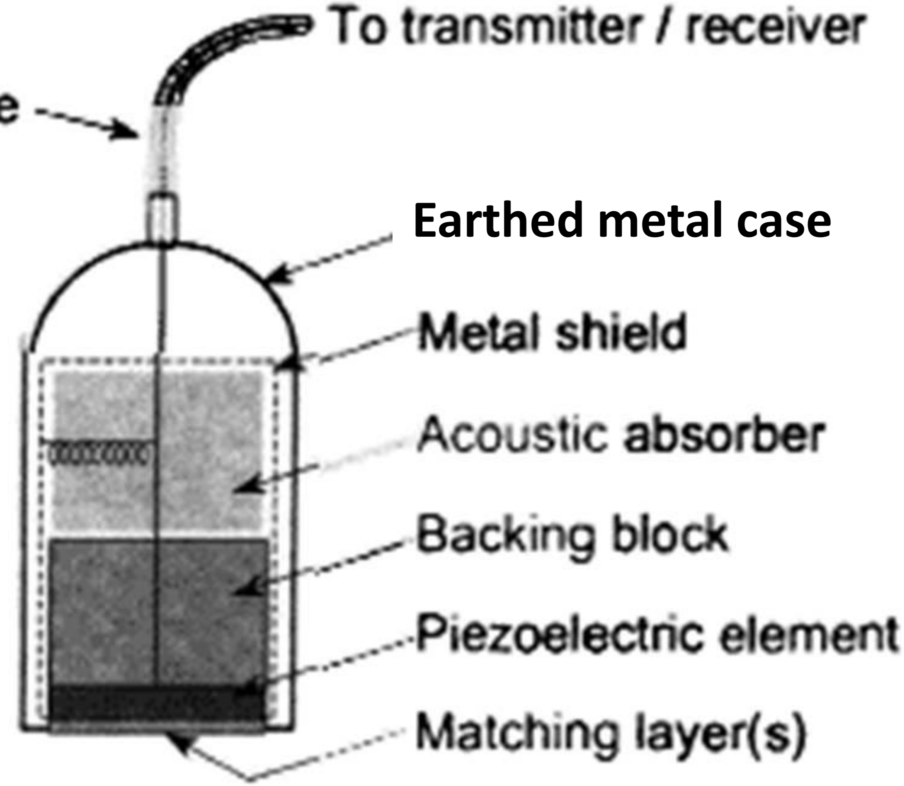


3- Succession of frames is sufficiently rapid to demonstrate tissue motion (real time imaging)





probe construction and types



Probe construction:

•**Piezoelectric element:**

In the transmitting mode:

- The energizing voltage is applied between the back face of the piezoelectric disc (via insulated wire) and the front face (via earthed metal case)

In the receiving mode:

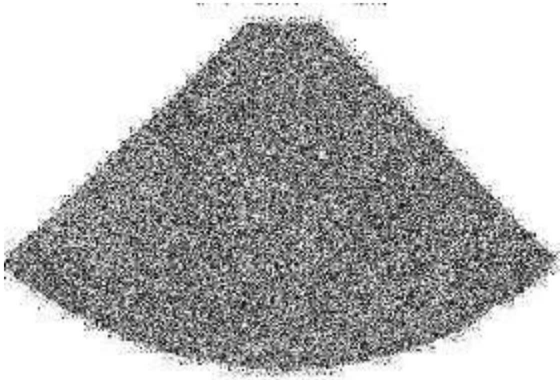
- Signal produced by the returning echo is led away along a wire

- **Backing block:**
  - made of epoxy resin in which are suspended fine particles of tungsten
  - Matched to the transducer (admit backwards travelling waves which is then absorbed within the block) → ……… Pulse , and ……… Q
- **Matching layer**
  - Decrease U/S reflection
  - Protect the disc

Types of probes

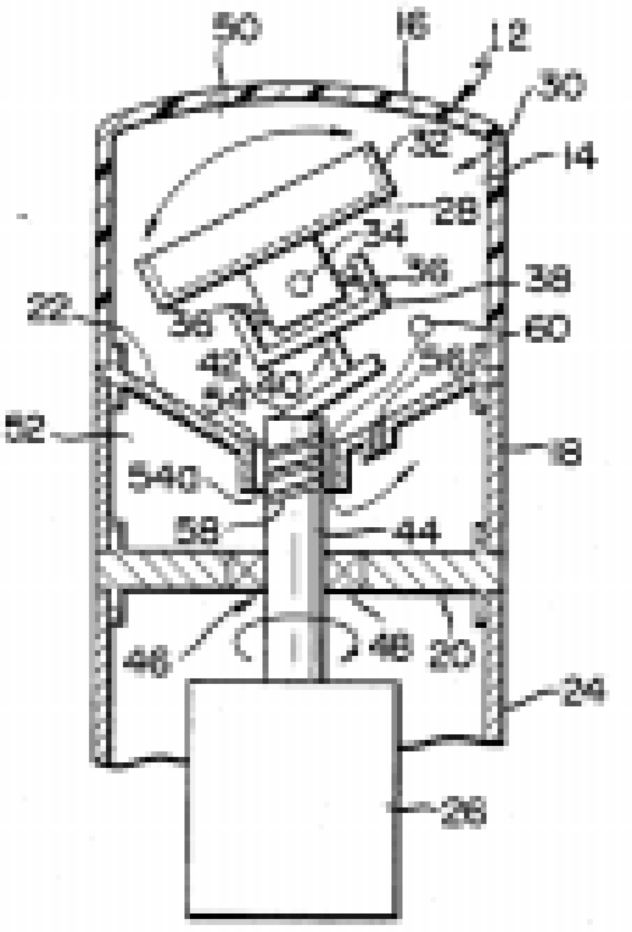
- 1) mechanical probes: probe has moving parts that oscillate
- 2) electronic or phased probes: no moving parts

Mechanical probes



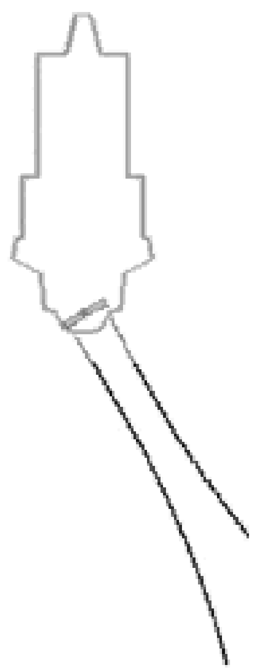
1) mechanical sector probe:

- Contains single piezoelectric element
- Crystal is attached to a motor that mechanically move it back and forth
- Each sweep = image frame
- Rate of oscillation (and frame rate) can be varied
- Ultrasound beam geometry is that of a sector
- Sector angle (and so field size) can be varied



2) rotating head transducer

- One or several transducers crystals are mounted on a cylinder that is rapidly rotated over 360º using a motor

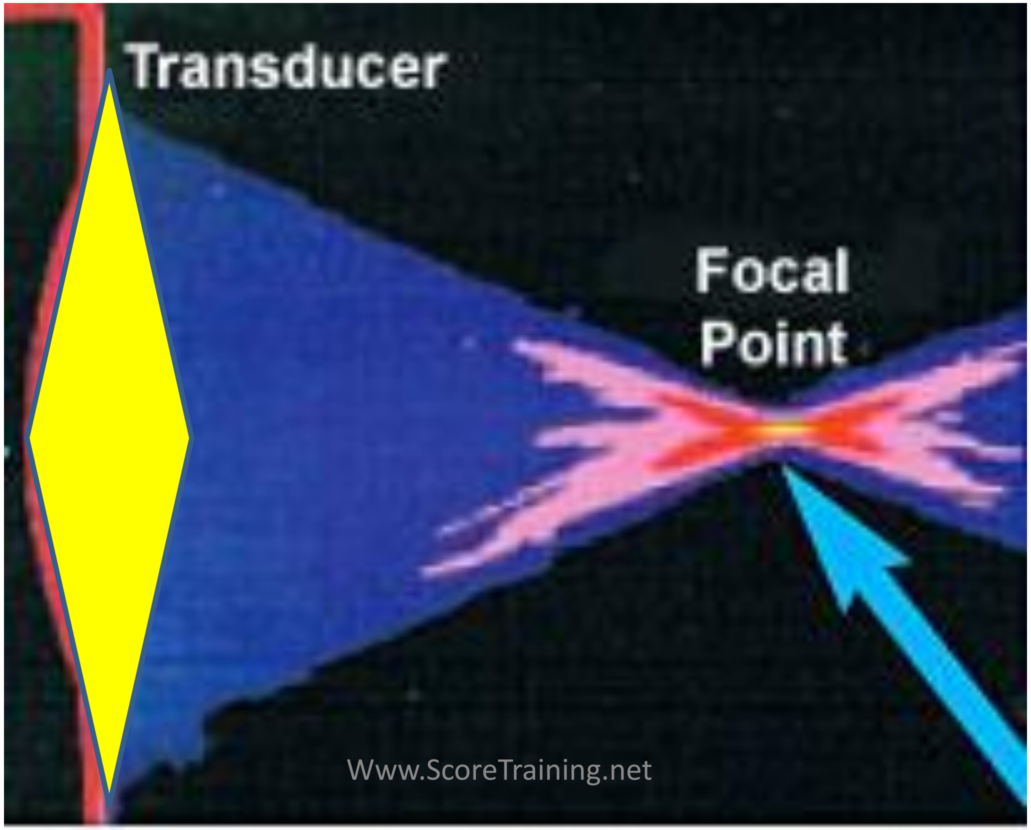


3) mechanical probes with rotating mirrors:

- Transducer crystal is steady
- Rotating mirror reflect the sound beam and direct it out of the probe

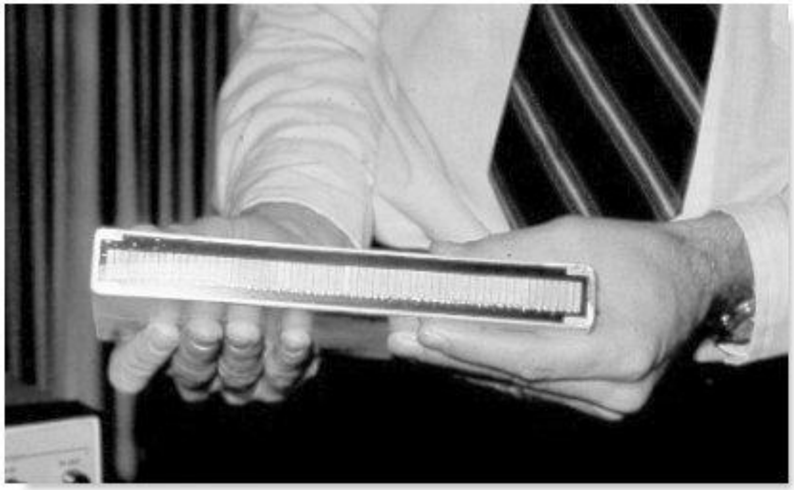
mechanical probes Focusing (mechanical focusing):

- Using acoustic lens or curved mirror
- Creates a beam with fixed focal length specific for each probe
- Transducers may have strong , intermediate or weak focusing
- The price of short focal length is increased divergence of far field



Electronic probes = annular arrays

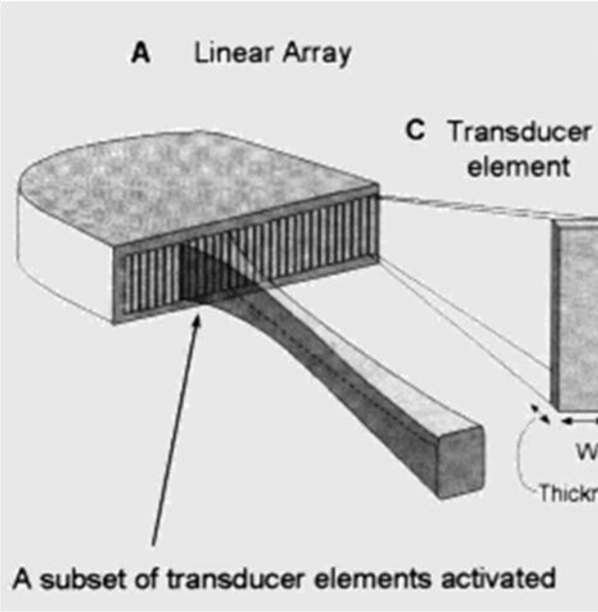
- Crystals are arranged in arrays
  - i.e. row of several small transducers
- Each crystal can transmit or receive individually
- Sweep ,focusing and steering of the beam is controlled by timing patterns



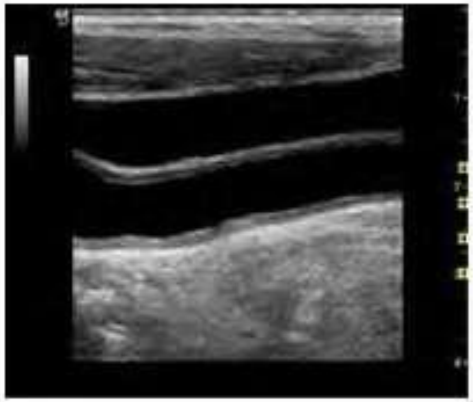
Types of electronic probes

1) sequential (stepped) linear array:

- Elongated transducer divided into large number of separate narrow transducer elements (about a wavelength in width)
- Individually they produce poor beam with short near field and widely divergent far field
- They are energized in overlapping groups in succession (1-6 , 2-7 , 3-8….)
- Results
  - At each given time a well defined ultrasound beam scan a rectangular area in the body
  - Formation of rectangular shaped images

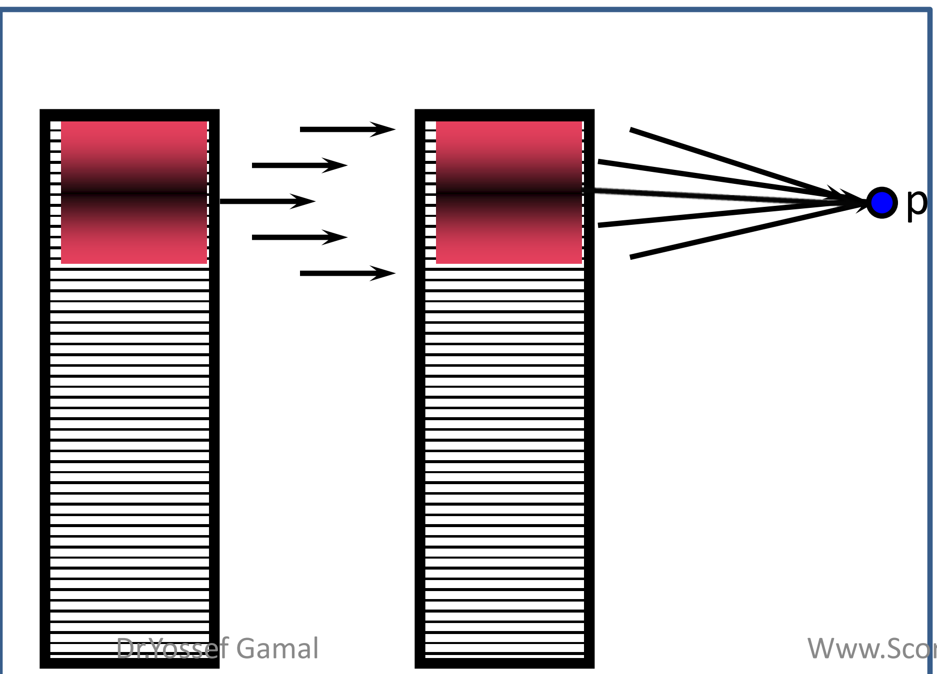


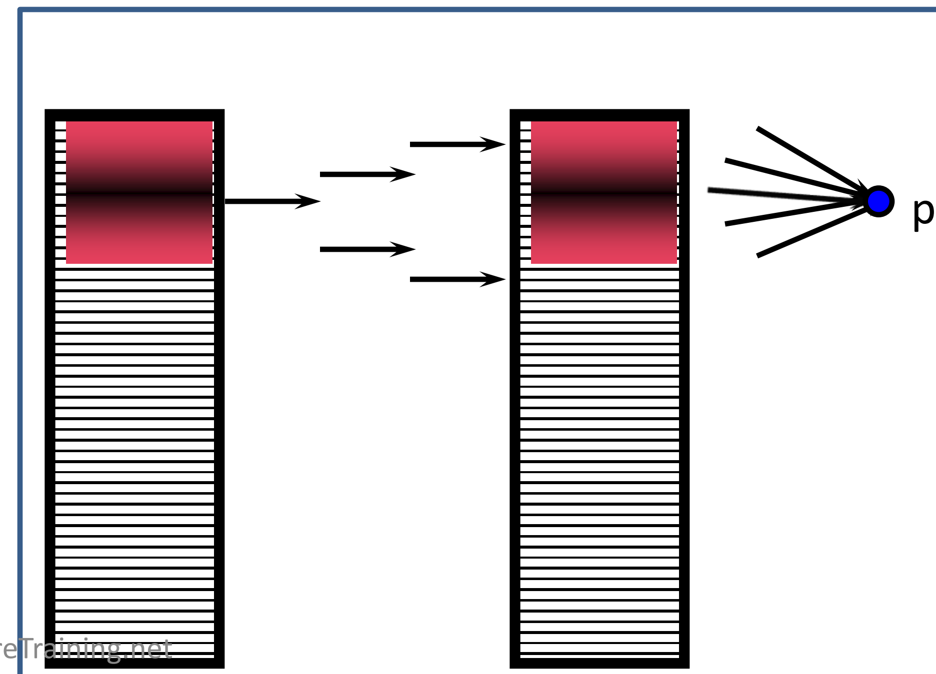
Rectangular images



Electronic focusing in stepped linear array:

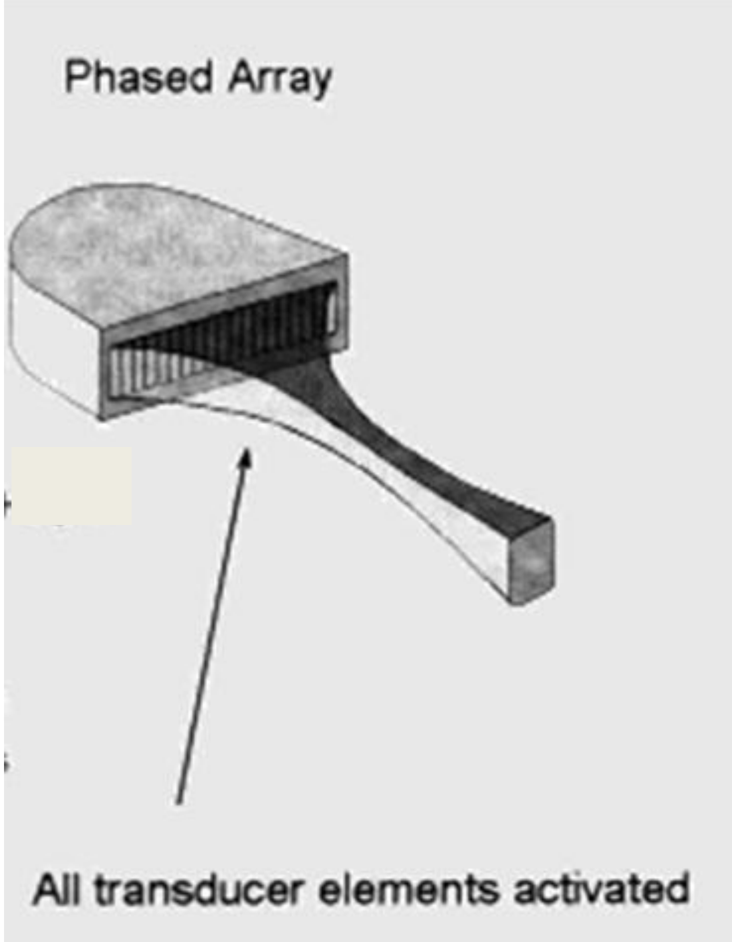
- Each group of crystals are not energized in exactly the same time
- Outermost pair is energized first , then after a very short delay the next pair , and finally the innermost pair
- Result
  - All pulses arrive at the point p (focal point) at the same time and reinforce
- Focal depth can be alter by the operator: the greater the time delay between energizing successive pairs of elements , the shorter is the focal length



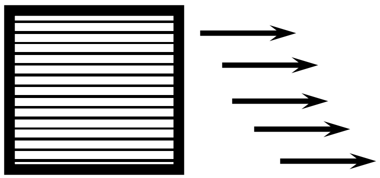


2) steered or phased sector linear array:

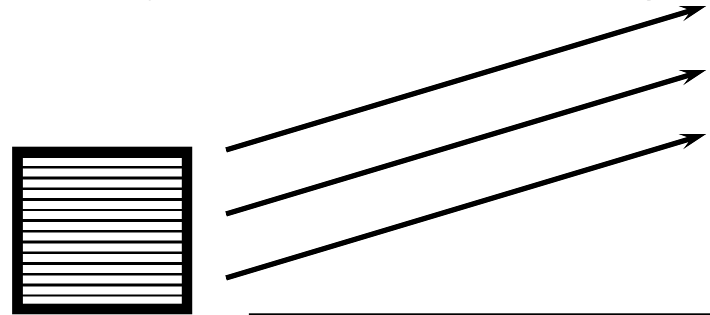
- Similar but shorter transducer (contains fewer elements)
- Transducers work all together (compare to the previous type)
- if all elements energized simultaneously → beam travel forwards



If Elements energized separately in rapid sequence (1,2,3…) → pulses reinforce only in one direction (interfere destructively in all other planes) = beam steering

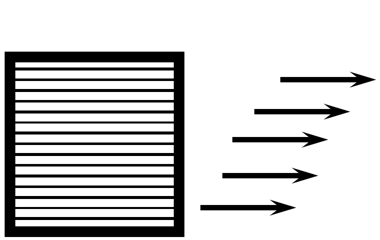


timing variations.

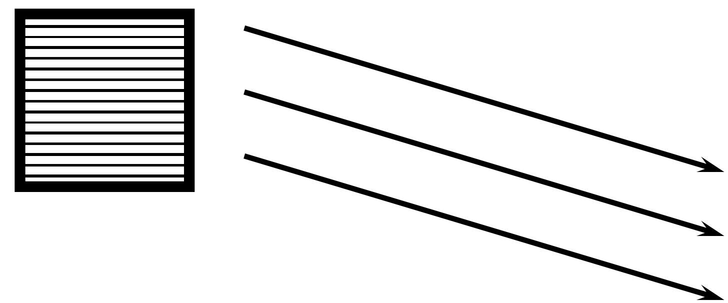


Beam steered upward

If this process is reversed → steering in the opposite direction



timing variations.



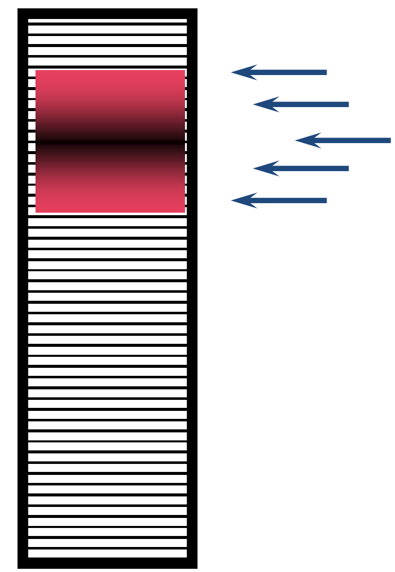
Beam steered downward

By changing the time delay in the successive sequences → scan line is swept across the patient covering a sector field (remember mechanical scanning?)

Focal point can be changed by the adjustment of phase delay pattern

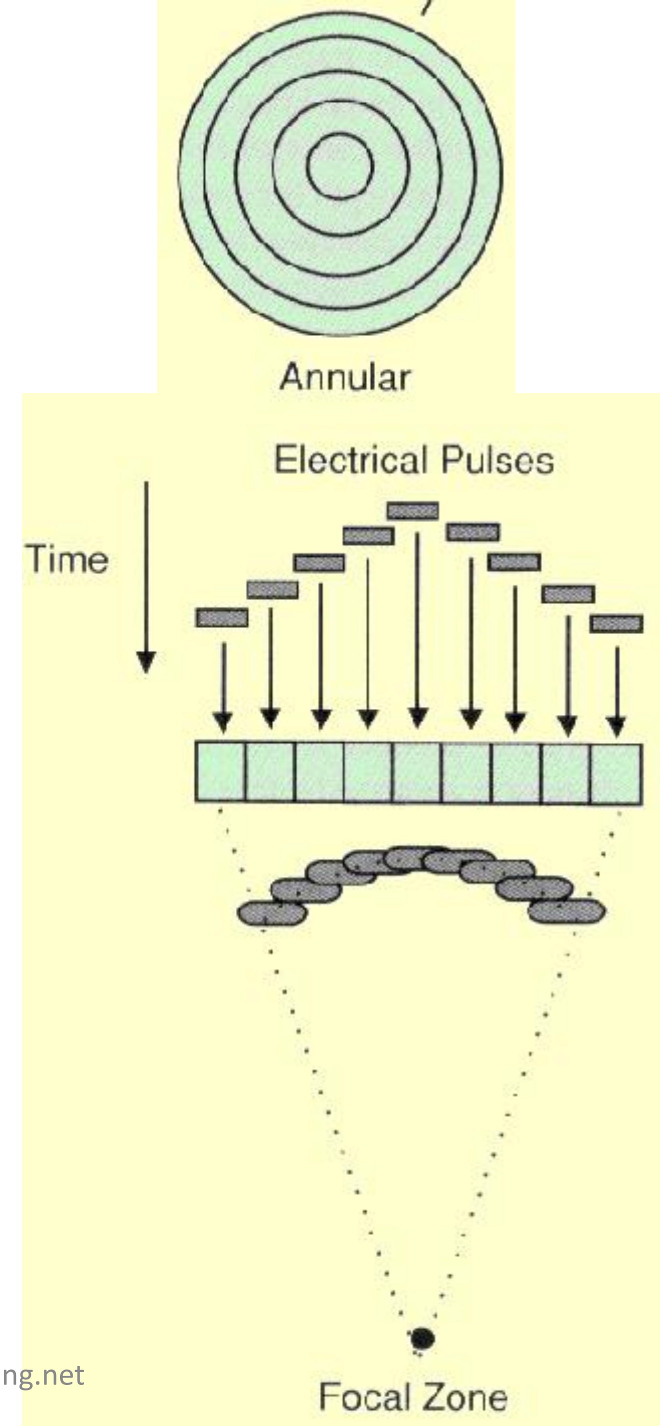
N.B: Listening direction can be also steered & focused similarly

- appropriate timing variations applied to echoes received by various elements of a group
- listening focus depth can be changed electronically between pulses by applying timing variations as above

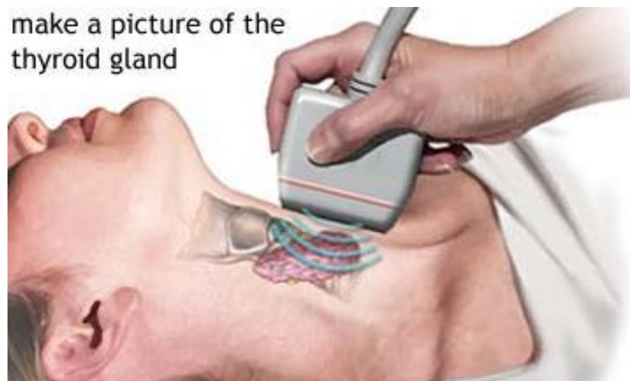


3) phased annular array:

- Five to ten Circular shaped crystals arranged concentrically
- Focusing of annular arrays:
  - Outermost ring is energized first , followed by subsequent rings , and finally the central element

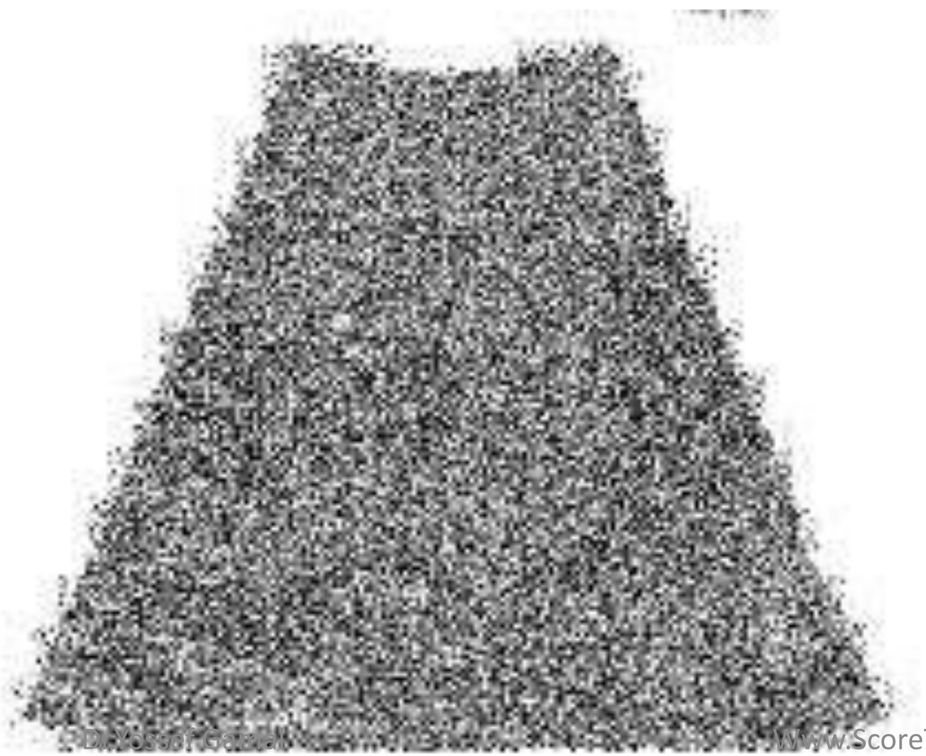


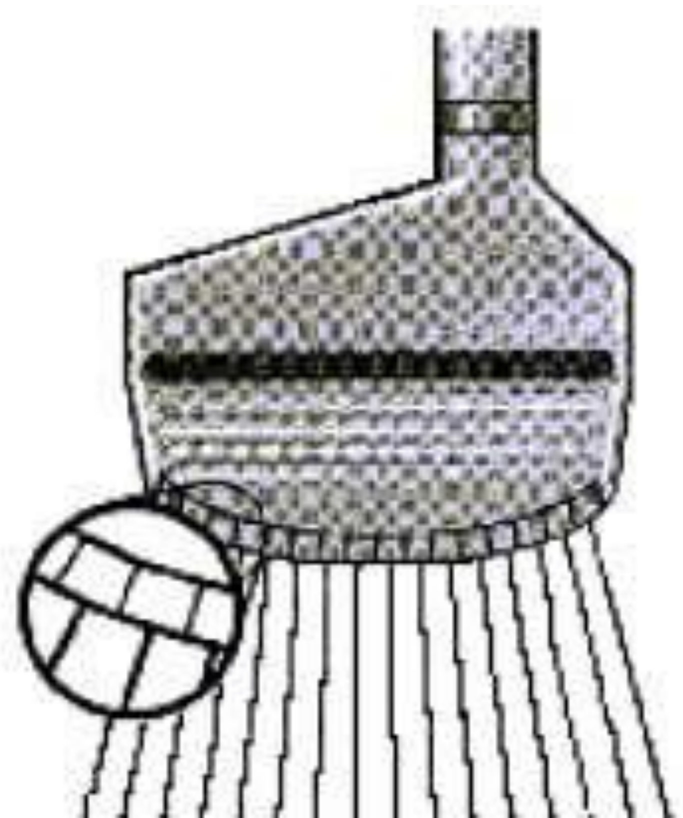
	Stepped Linear scanner	Sector (phased) scanner
Patient contact area (acoustic window required)	Large	Small
Image quality	Better	Less
Field of view need skin	Wide	Narrow
Field at Depth	Relatively narrow	wide
Uses	Abdomen , thyroid obstetrics	Neonatal brain, scanning the heart through intercostal space



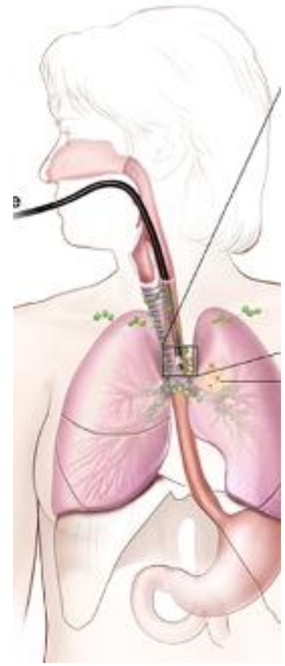
N.B: Convex linear stepped array:

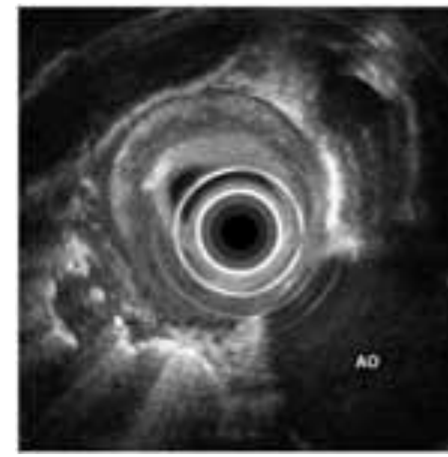
- Same as linear stepped array but the face of the probe is curved into arc shape → sector type image (wide view at depth)
- advantage: no complications of beam steering (no loss of focus at edge) because scan lines are perpendicular to the array surface
- Disadvantage: at depth there are diversions with reduced line density





	Mechanical scanners	Electronic scanners
cost	cheaper	more
resolution	better	less
Moving parts	Yes	no



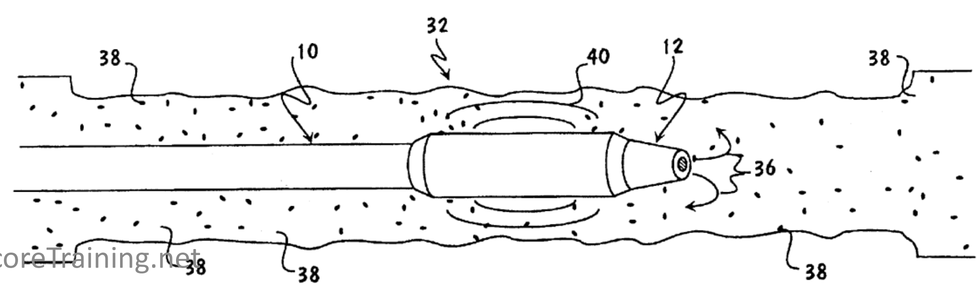


N.B: Endoscopic ultrasound:

- advantage: avoid effects of bone or gas
- Types : single high frequency transducer rotating through 360^o
- Examples: trans-esophageal ECHO , Trans-rectal prostatic ultrasound

Trans-vascular transducer:

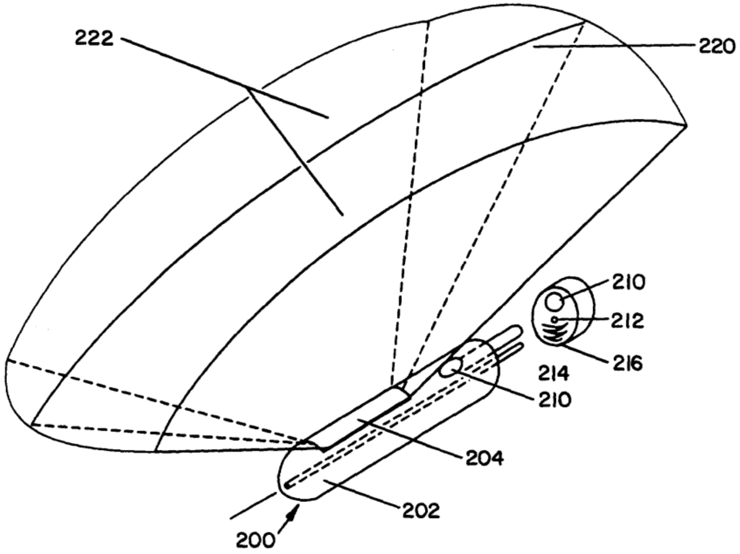
- very small crystal array at the end of the vascular catheter
- Operate at 10-20 MHz

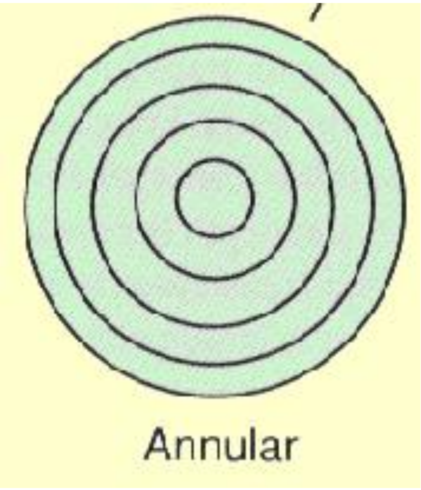


Ultrasound electronic focusing in different planes

1) azimuthal plane:

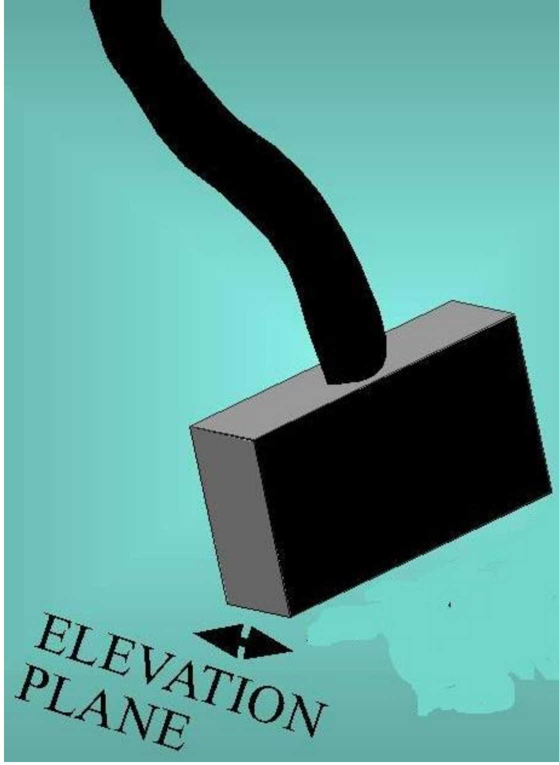
- The plane parallel to the length of the probe
- Electronic Focusing is Possible with both linear and annular arrays

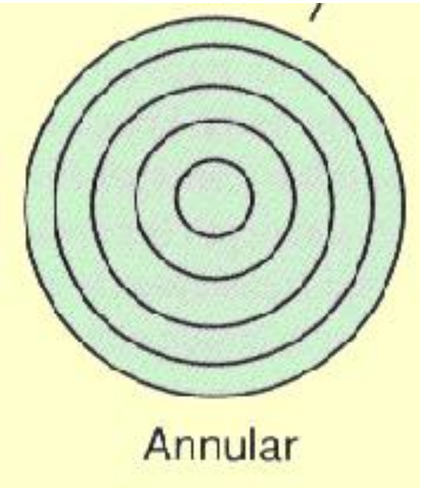




2) Elevation plane:

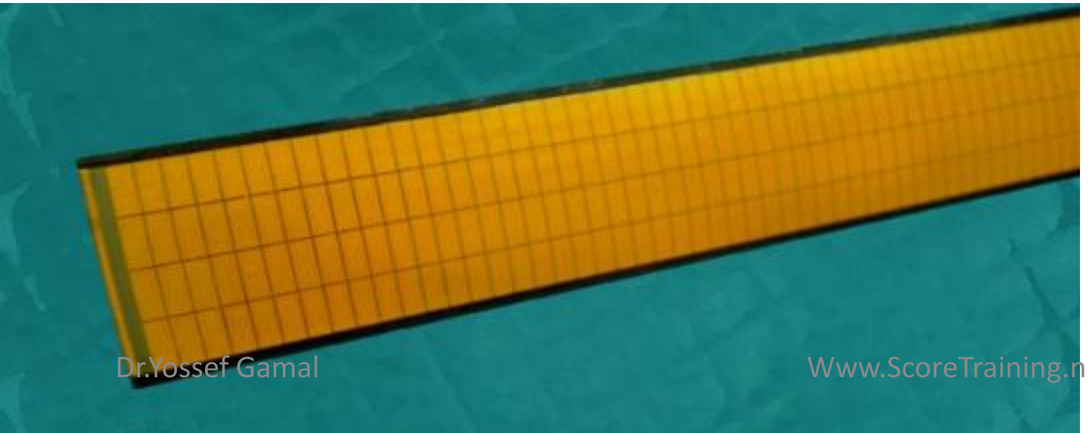
- The plane perpendicular to the long axis of the probe
- Focusing in that plane Define the slice thickness
- **linear array:** Electronic focusing in this plane is Not possible (done by shaping each transducer or by lens)
- **Annular array:** can be done

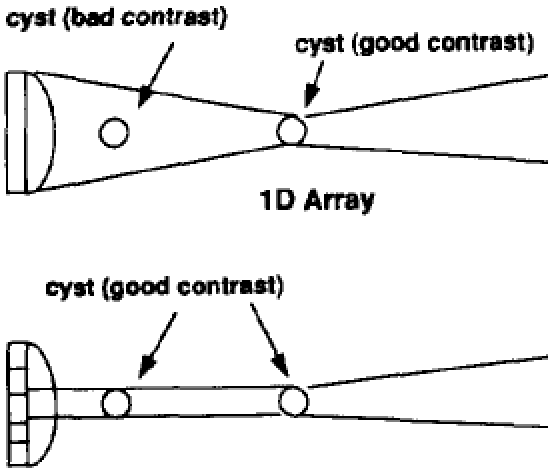




New 1.5D transducers:

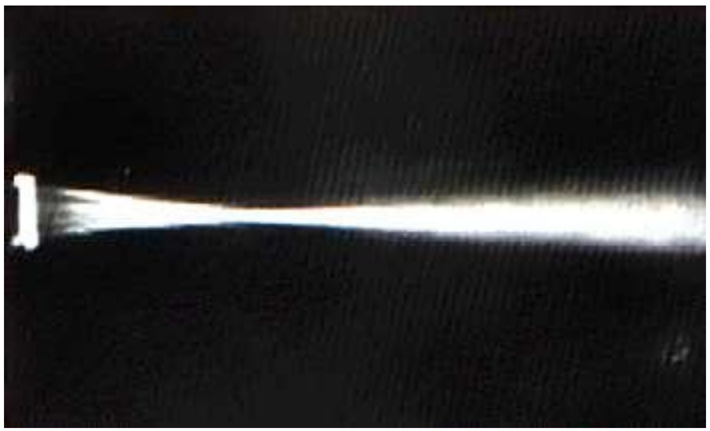
- Seven rows of small elements replace single row of conventional linear array
- Focusing in the 2 planes can be done
- Element selection is used rather than beam steering
- Produce better resolution of small lesions
- Produce greater uniformity at depth
- Inter row spacing = 10 λ
- Inter-element spacing = λ/2

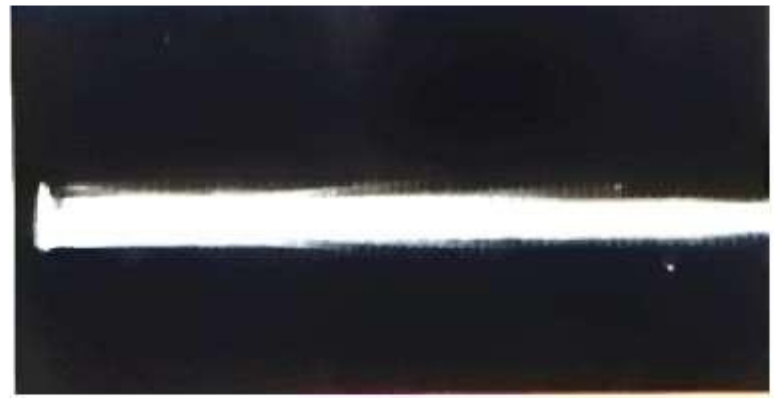




Problem: focusing of the beam improve the image in the focal region , but make it worse beyond it

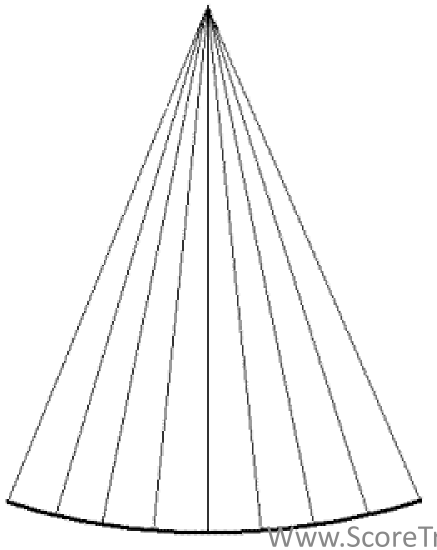
Solution: Multiple zone focusing

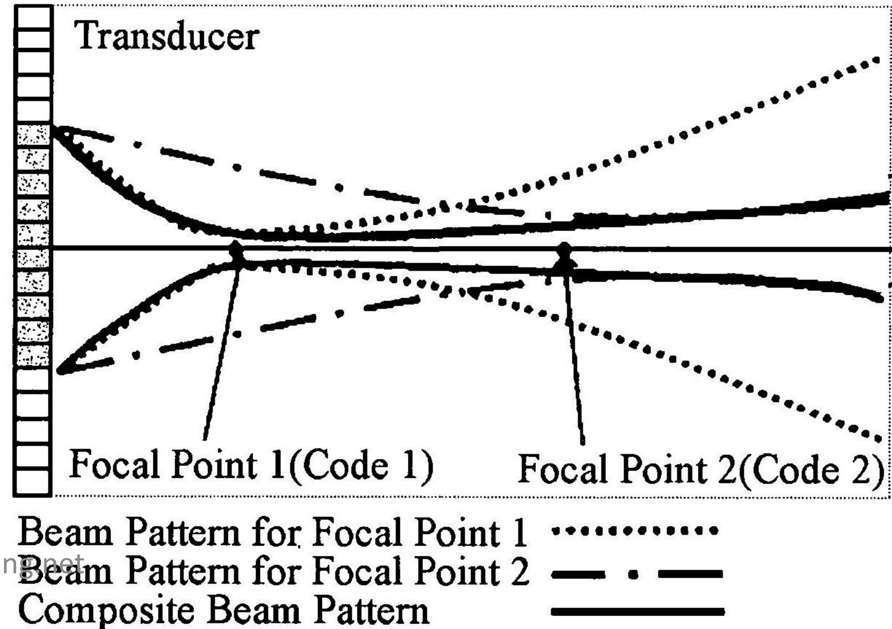




Multiple zone focusing

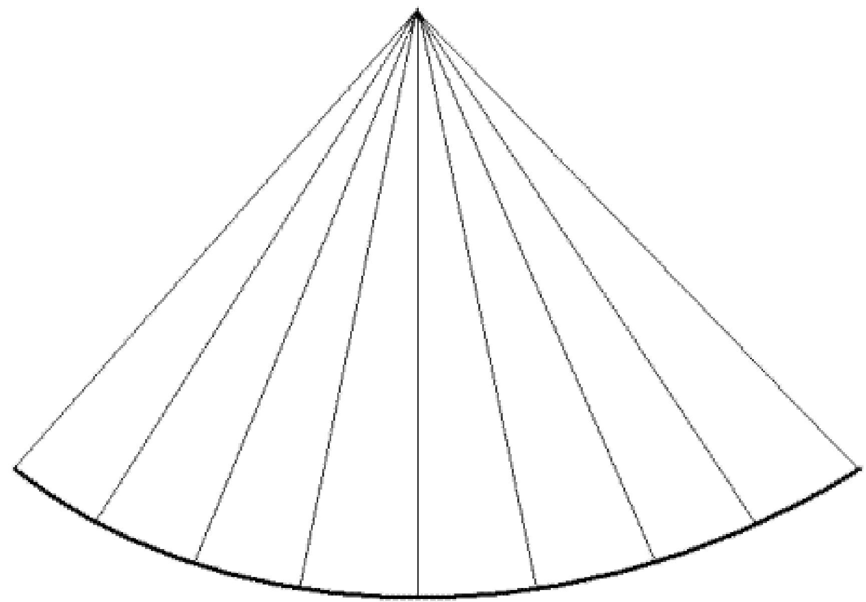
- **Method:**
  - along each scan line , more than one pulse are sent in succession
  - In each pulse, the phase delays are altered to focus at different depth
  - This is done for both transmission and receiving)
- **Advantage:**
  - focal zones overlap producing good resolution at deep and superficial area
- **Disadvantage:**
  - Decrease frame rate

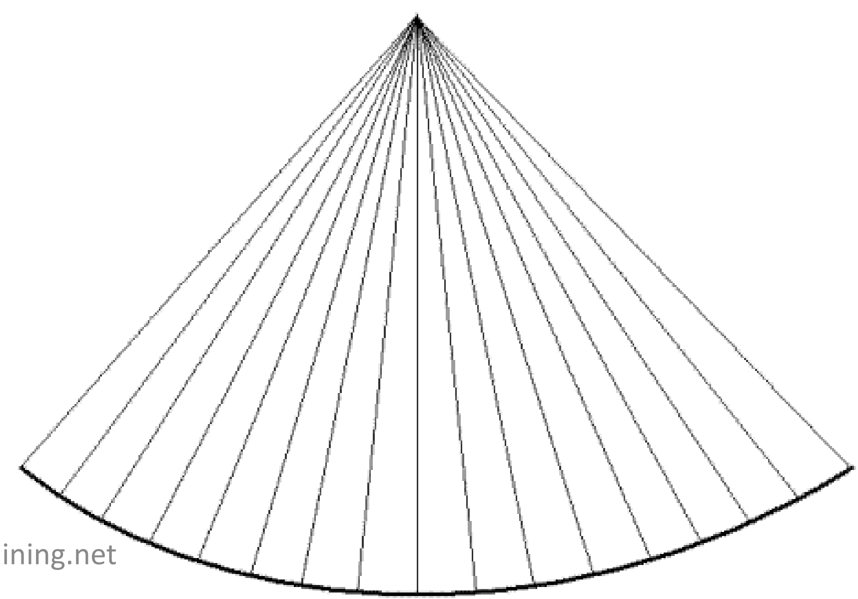




Scan line density

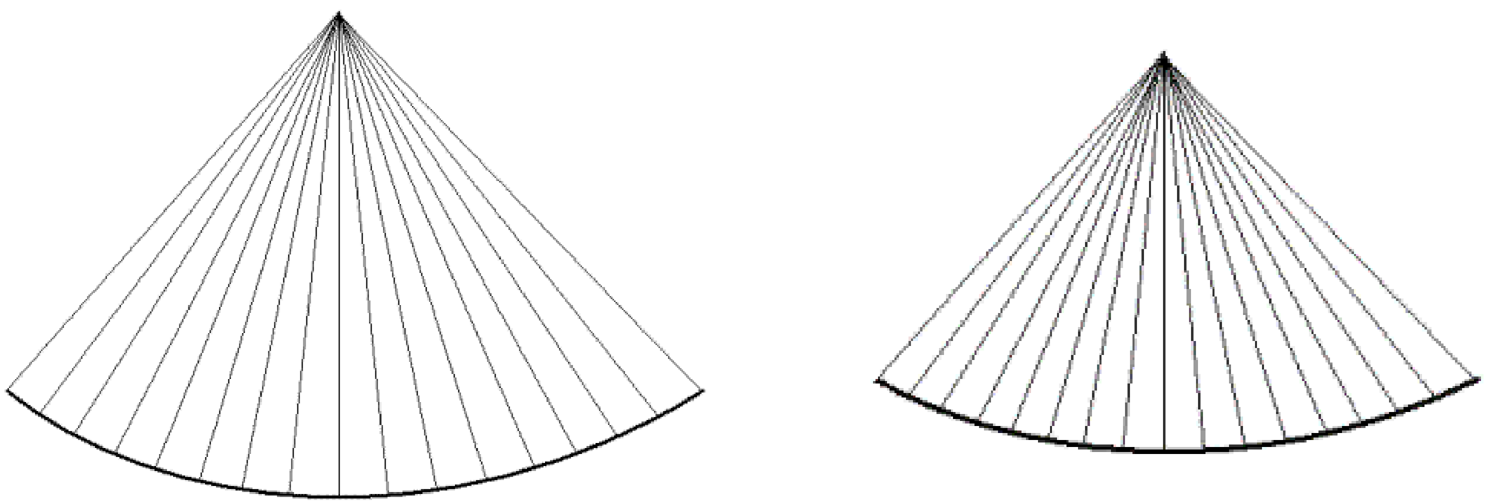
- Number of scan lines per frame
- Depends on the number of elements in the array
- ↑scan line density →↑image quality and resolution
- 100 lines/frame is usually sufficient (as lateral resolution is dependant on other factors)



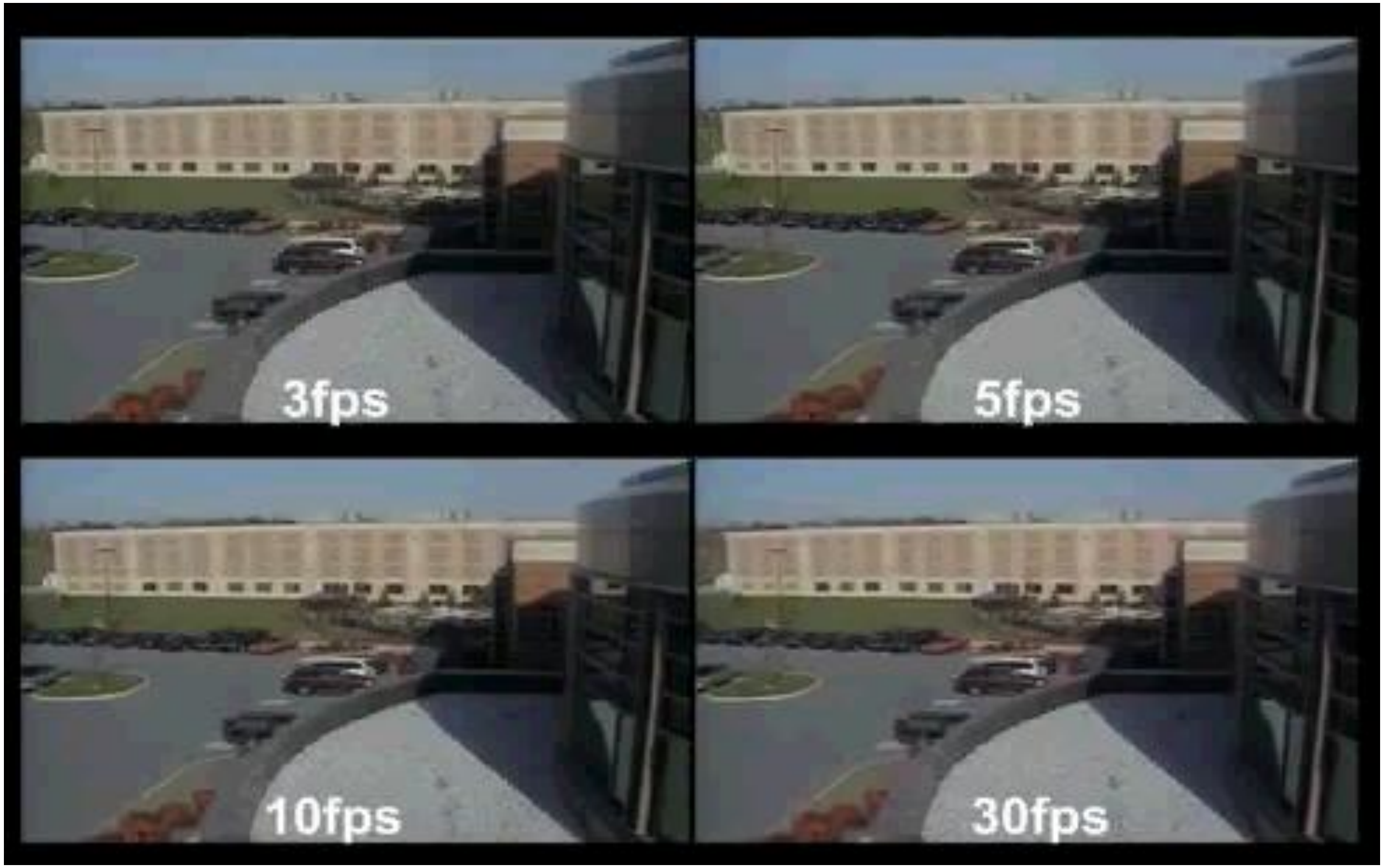


Frame rate

- Number of frames displayed per second
- ↑frame rate → better following of moving structures



Which has less frame rate?

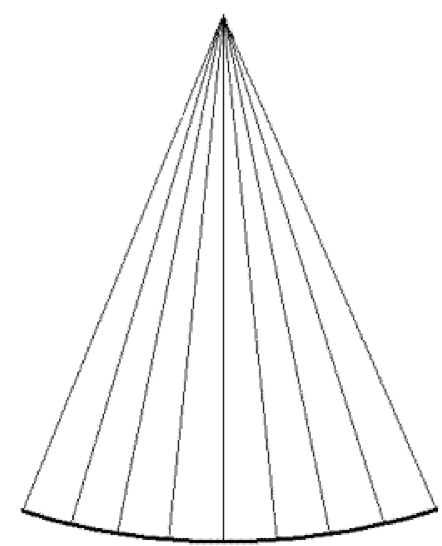


Important equation

Pulse repetition frequency (PRF) =

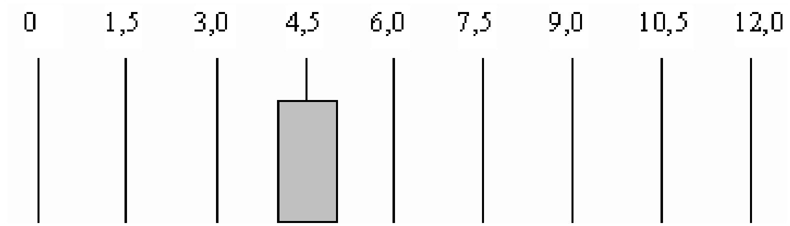
Frame rate x scan line density

Example: to achieve
Frame rate = 30 frames/s
With 100 lines per frame
We need PRF of ………………MHz



Depth of view

Depth of view = 0.5 x sound velocity / PRF



Explanation:

When the next pulse is generated , the previous pulse must make the complete return journey (from and to the transducer)

Pulse repetition frequency (PRF) =

Frame rate x scan line density

and

Depth of view = 0.5 x sound velocity / PRF

So that

Depth of view x scan line density x frame rate = constant

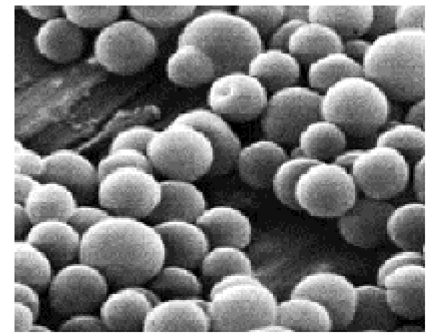
i.e. it is not possible to achieve both high frame rate with high scan line density (need high PRF), and in the same time scan at large depth

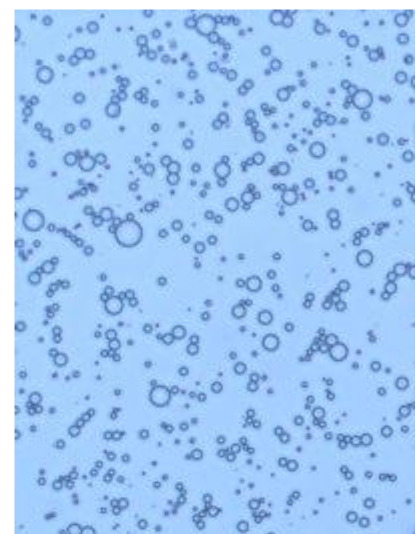
i.e. one aspect must be compromised

Ultrasound contrast agents

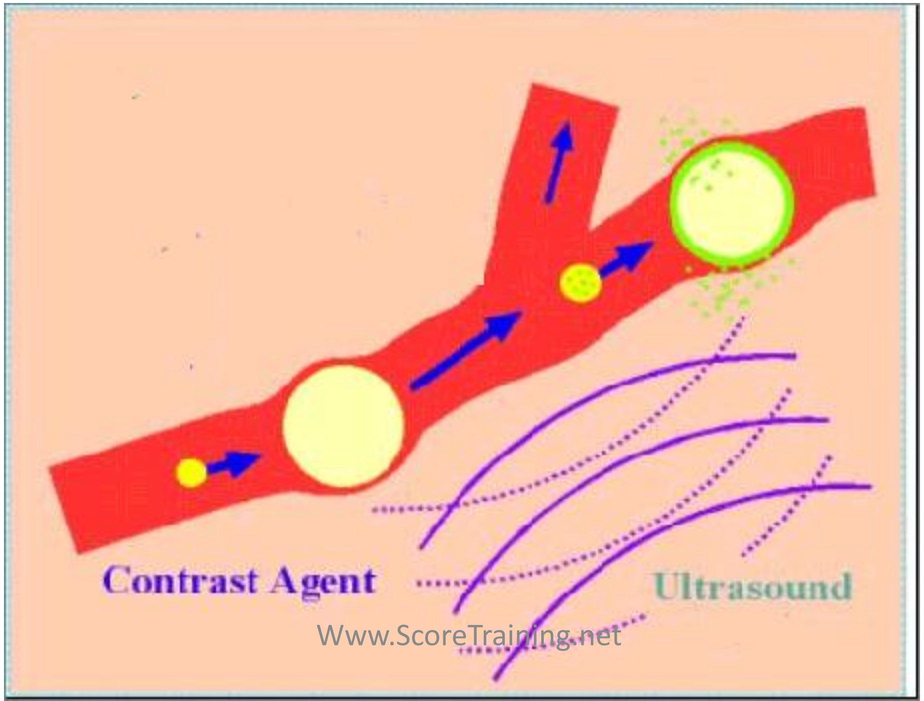
Ultrasound contrast agents

- **Advantage:** improve ultrasound image quality
- **Must be:**
  - of low toxicity
  - Readily eliminated from the body
- **Size:**
  - micro-bubbles: less than 4 µm
  - Nanoparticles: less than 1 µm



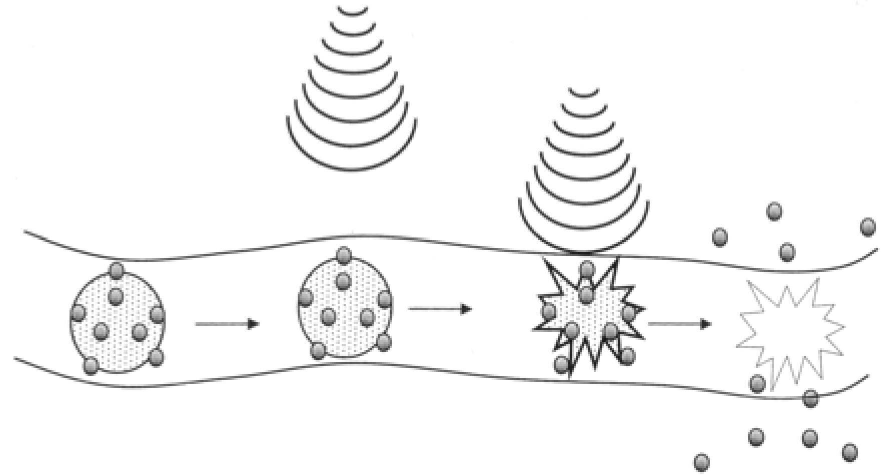


- **Mechanism of action:**
  - increase reflections from tissues containing the contrast agent
  - Although smaller than U/S λ, they can resonate at U/S frequency and at harmonic frequencies, enhancing echoes from the tissue of interest
  - After exam.: normal static diffusion leads to total bubble destruction within few hours



- Examples:

1- ultrasound-targeted microbubble:



- contrast agent with attached bioactive substance will distribute in capillaries of target organ.
- U/S then destroy microbubbles , releasing the substance into surrounding tissue.

2- air filled microspheres encapsulated in a thin shell of albumin:

- Increase backscatter from ventricular border → increase visualization
- adhere to thrombi , assist in DVT diagnosis

3- Low solubility gas encapsulated in lipid shell:

- Used in all vascular applications (assist in visualization of small vessels)

4- per-fluoro carbon nano-particles:

- Slowly uptake by liver →improve metastasis visualization

5- Gold bound colloid micro-tubes:

- conjugated with Abs → immunologically targeted

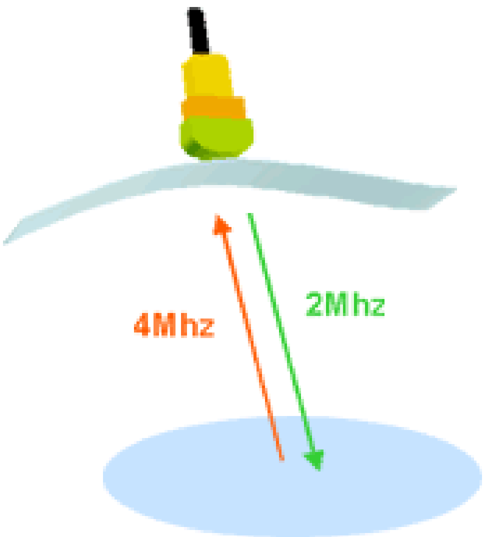
Harmonic imaging

Definition:

- imaging of harmonic frequencies = 2f , 3f, ...

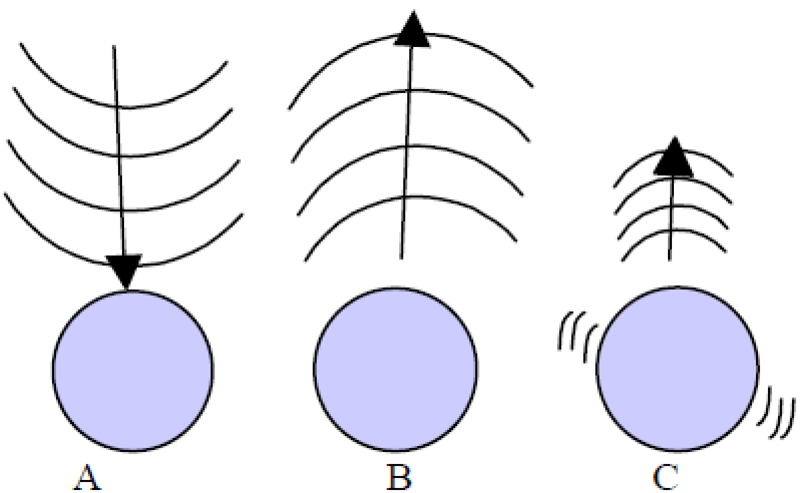
Generation of harmonics:

- Not generated by U/S scanner itself
- Generated in the body by two methods:



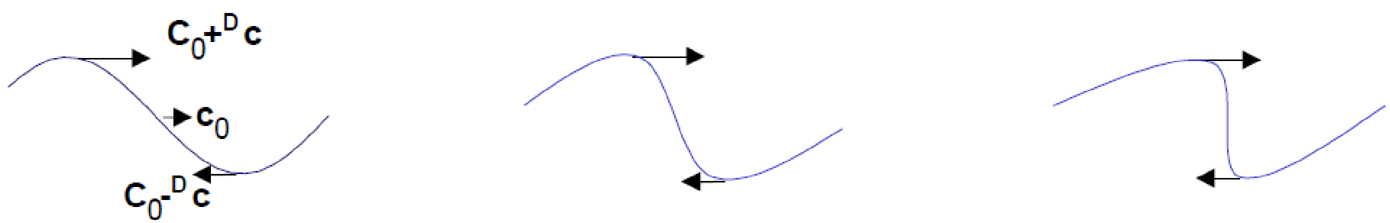
<u>1) Interaction with contrast agents</u>

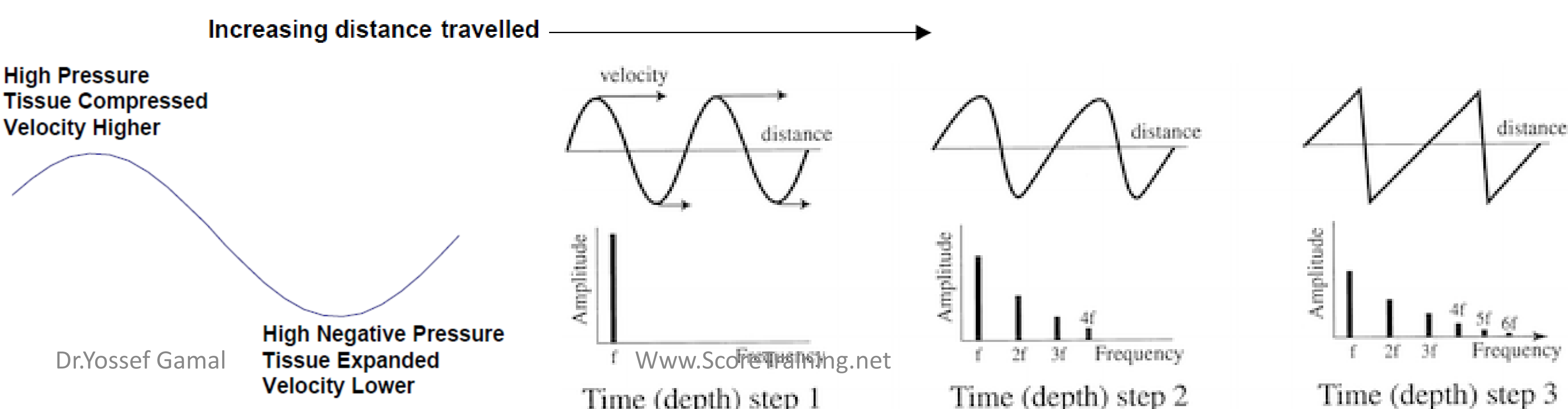
- When U/S pulse (with frequency f) encounter a bubble , there are two types of response:
  - Echo returns normally
  - Bubble vibrates in response to the shock from the pulse → this will generate a second harmonic a twice frequency of the original pulse (2f)
- Advantage: increased contrast of ultrasound image (2nd harmonic is received only from place of bubbles)



2) Interaction with tissues (tissue harmonics):

- When ultrasound pass through the tissue , it compress and expand the tissue
- When the tissue is compressed → ↑ sound speed
- When tissue is expanded → ↓ sound speed
- Result: top of the waveform is pulled forwards as the wave pass through the tissues → distortion with generation of harmonics (change in U/S frequency)
- These changes become more pronounced with depth, and degrade the normal imaging process
- Distortion is more pronounced in fat tissues (especially in obese persons)
- The resultant a waveform contains both fundamental frequency (first harmonic = f) and subsequent harmonics (integral multiples of first harmonic i.e. 2f, 3f , 4f)

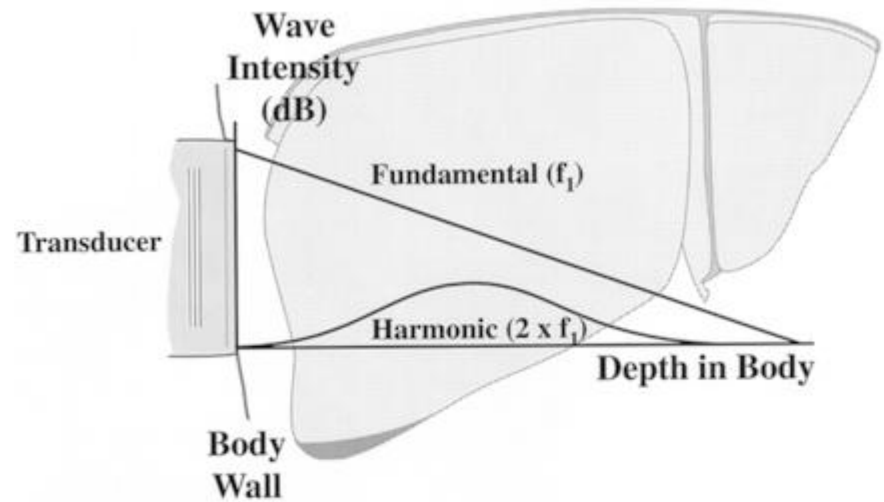


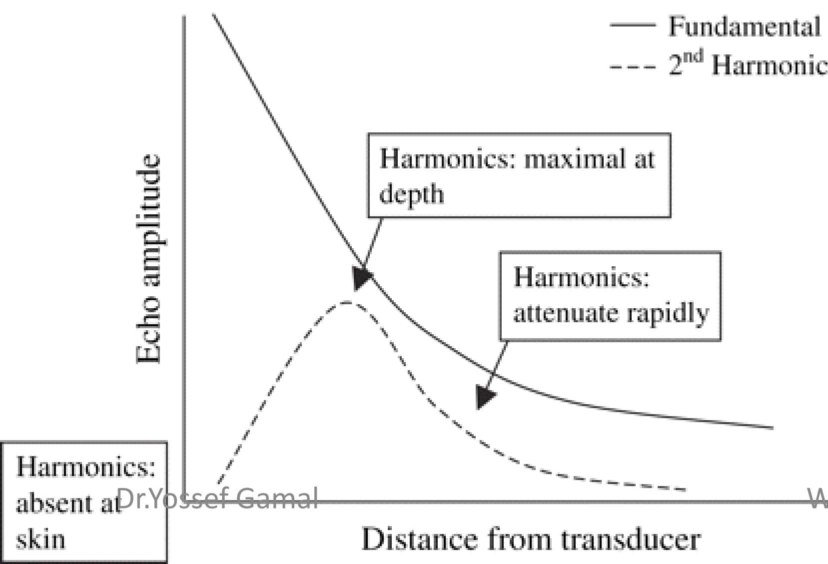


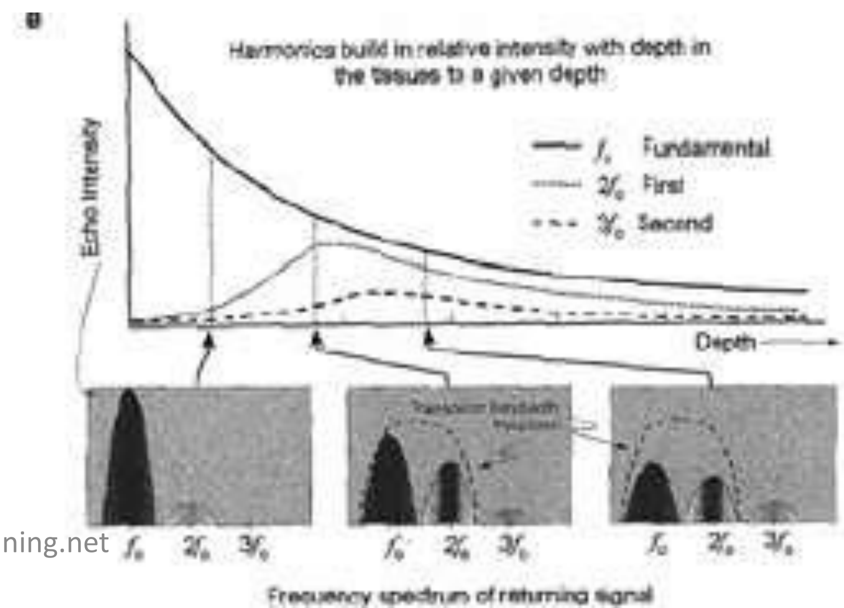
Harmonics are seen to varying degree throughout U/S field of view:

- Near field: no harmonics (signal has not traveled enough to distort)
- Near mid field: harmonics increasing (begin to be produced)
- Mid field: harmonics unchanging (generation = attenuation)
- Far mid field: harmonics decreasing (attenuation » generation)
- Far field : fundamental frequency only is present

- This means that harmonic imaging effect is most pronounced in the mid-field



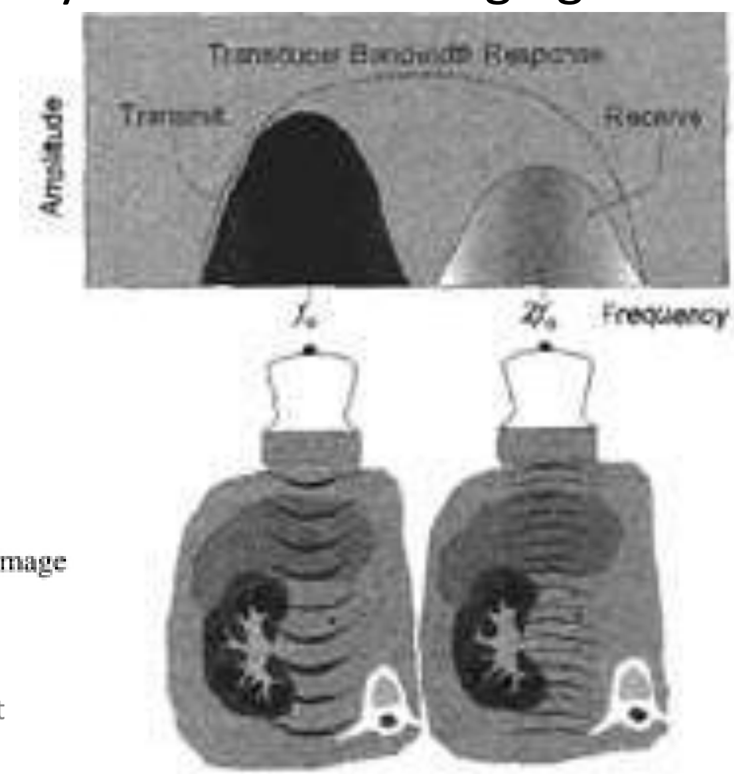


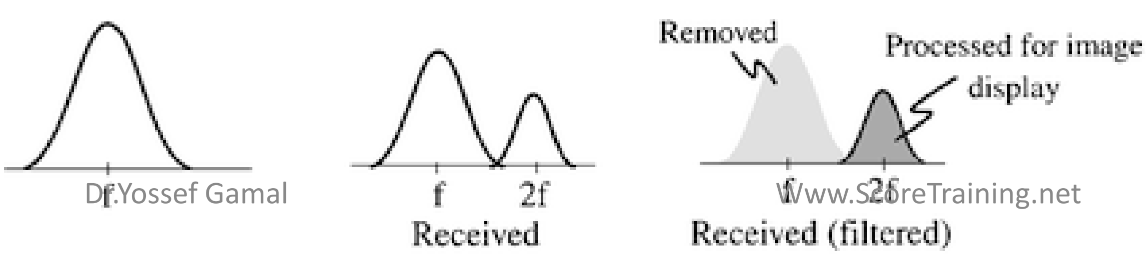


Methods of isolation of 2nd harmonic to form the image:

A) harmonic band filtering:

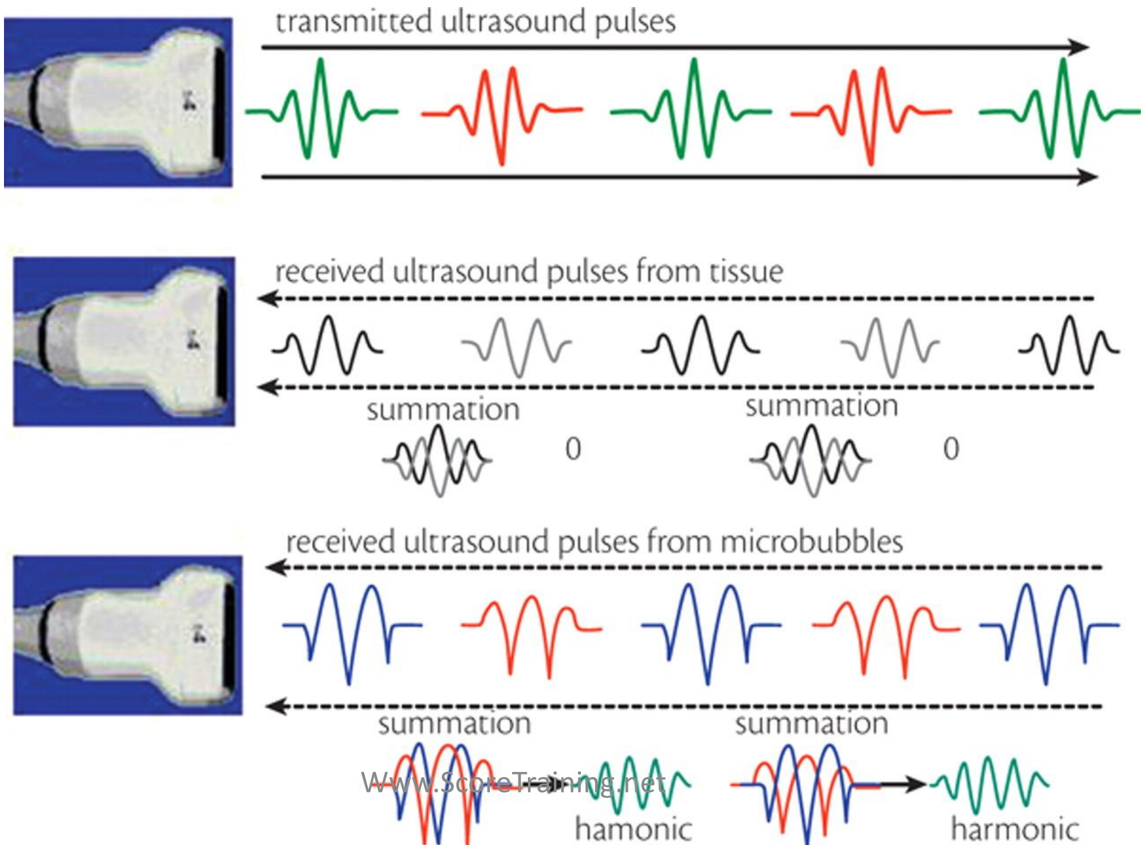
- Fundamental frequency is removed using filter , leaving the tissue generated harmonics to form the image
- transmitted pulse should not contain higher frequencies (this could corrupt the received signal) , and the Pulse produced must have narrow bandwidth at lower frequency
- receiving bandwidth of the transducer cover frequencies of harmonics
- Disadvantage: decreased axial resolution (transmitted pulse has narrow ↓ f) , but this is compensated by the high quality of harmonic imaging





B- pulse inversion:

- Two pulses are sent with reversed polarity
- Echoes received from each pair of pulses are summed
  - Fundamental harmonics disappear (two received echoes cancel each other)
  - Amplitude of harmonics is doubled (↑SNR of harmonic)
- Disadvantage: motion artifacts (frame rate is two times slower)

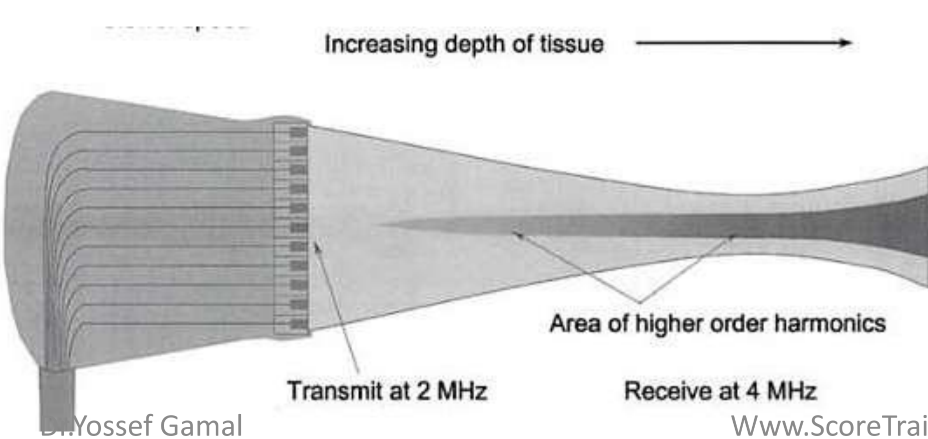


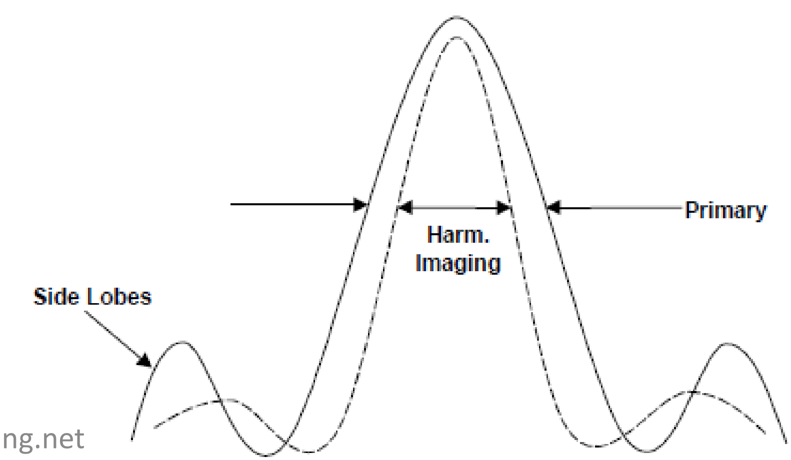
Advantages of harmonic imaging:

a) Harmonic beam is narrower than conventional beam

b) Side lobes are lower than conventional beam

- A & b → increase lateral resolution and contrast resolution



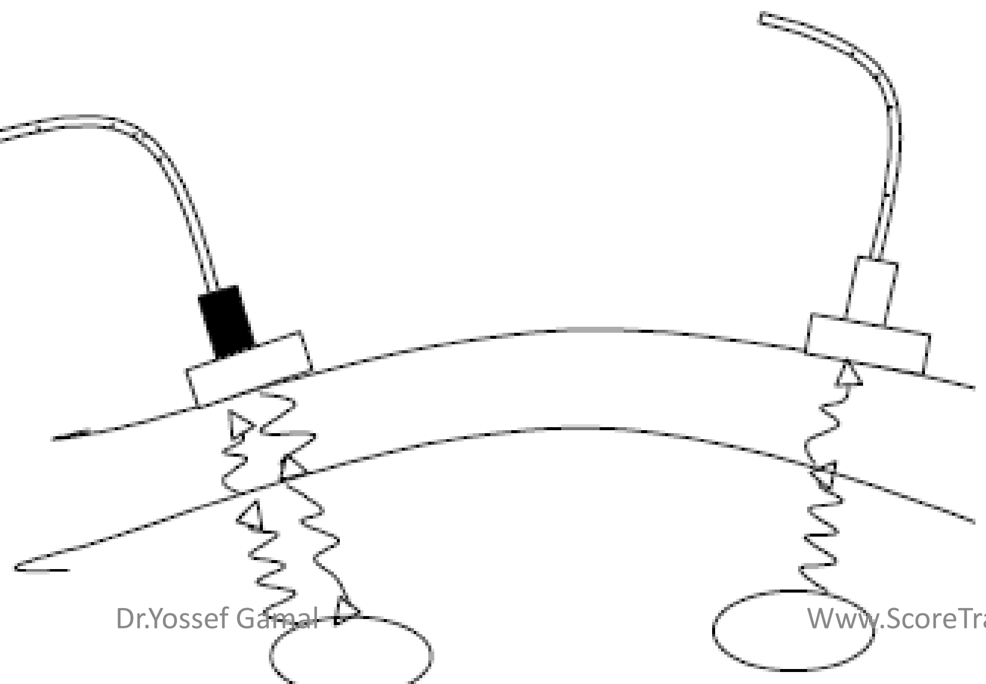


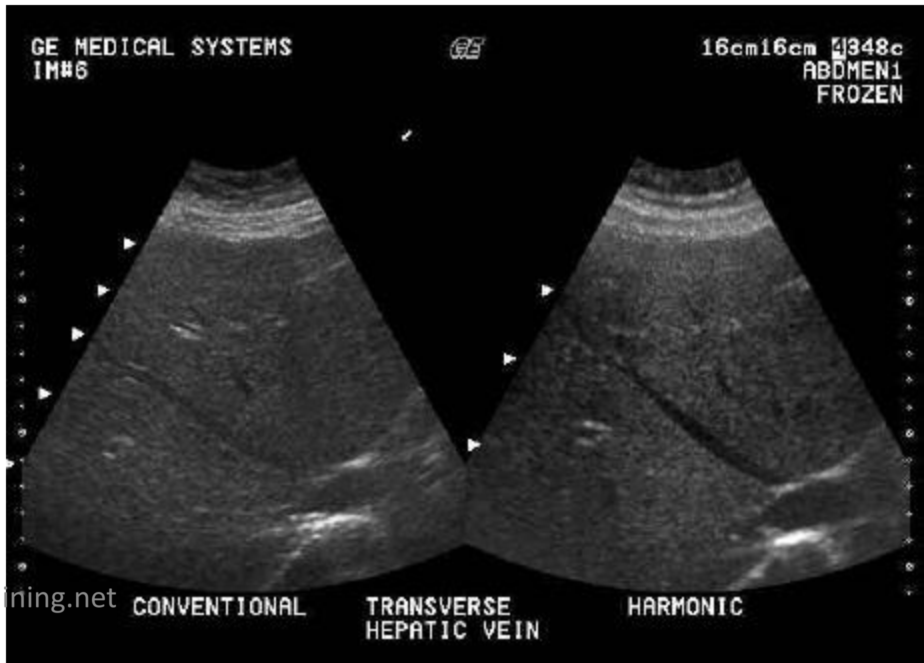
C) reverberation artifacts *(caused by subcutaneous fat)*, fatty tissue distortion and scattering are reduced :

– because 2nd harmonic pass through fat layer once only (during receiving) , not twice as fundamental frequency

d) Low acoustic noise →↑visualization of low contrast lesions

c & d → increase ↑ contrast resolution





3D and 4D ultrasound

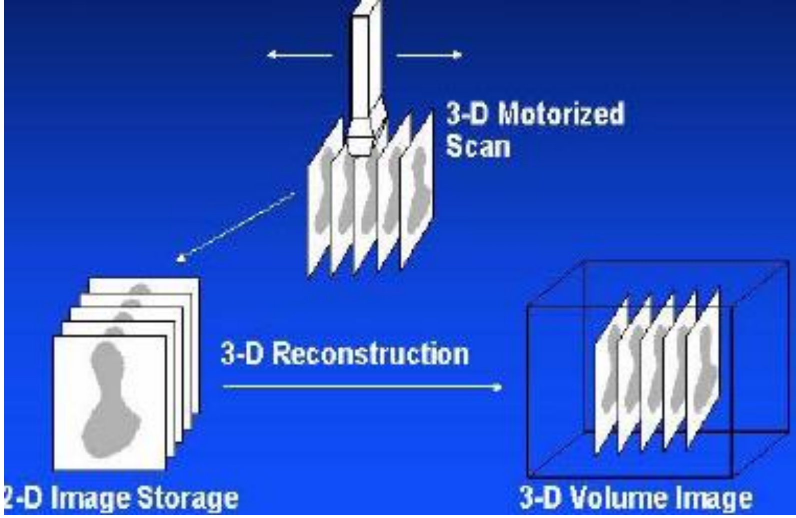
3D ultrasound

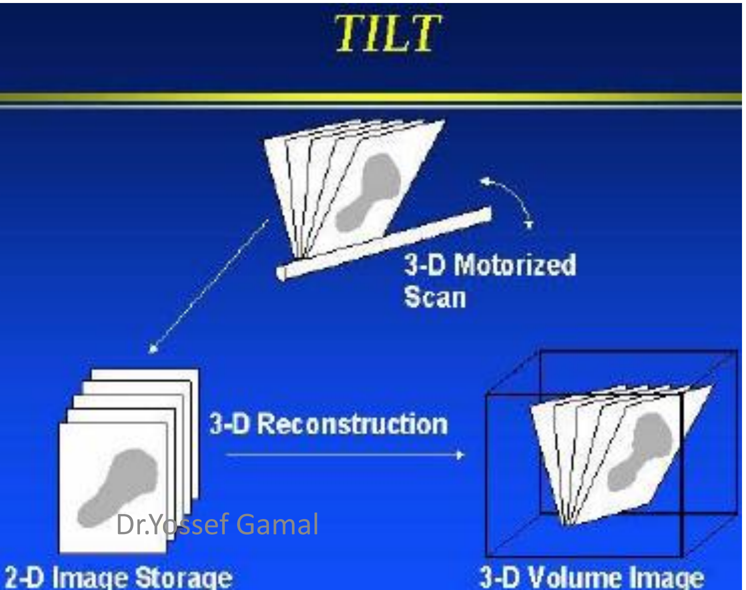
- Idea: obtained from a set of two dimensional scans

- Methods:

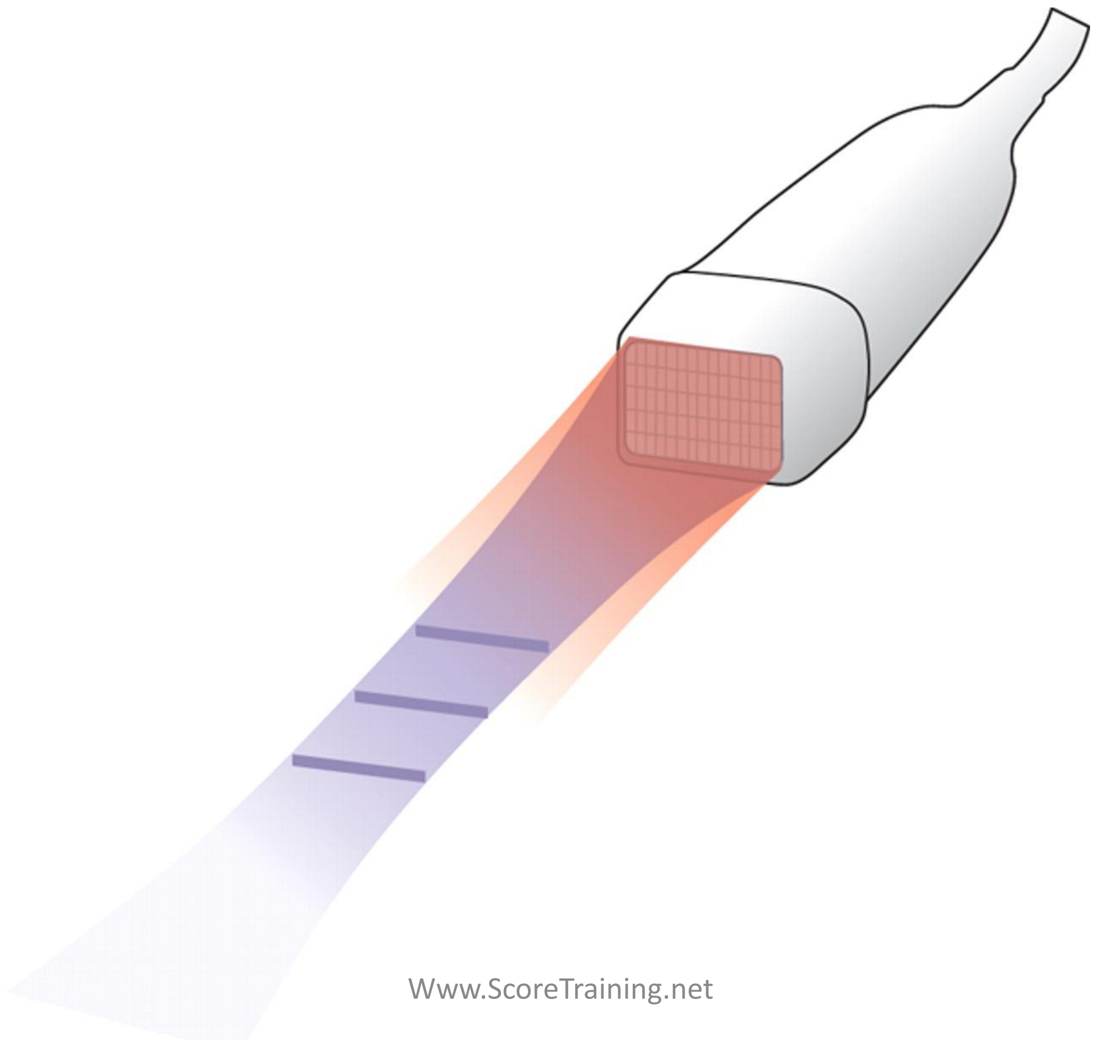
1- Electronically controlled probe movement in a 2D array

Disadvantage: Technique is slower than 2D scans





2- using a Rectangular array transducer =…………



4D ultrasound

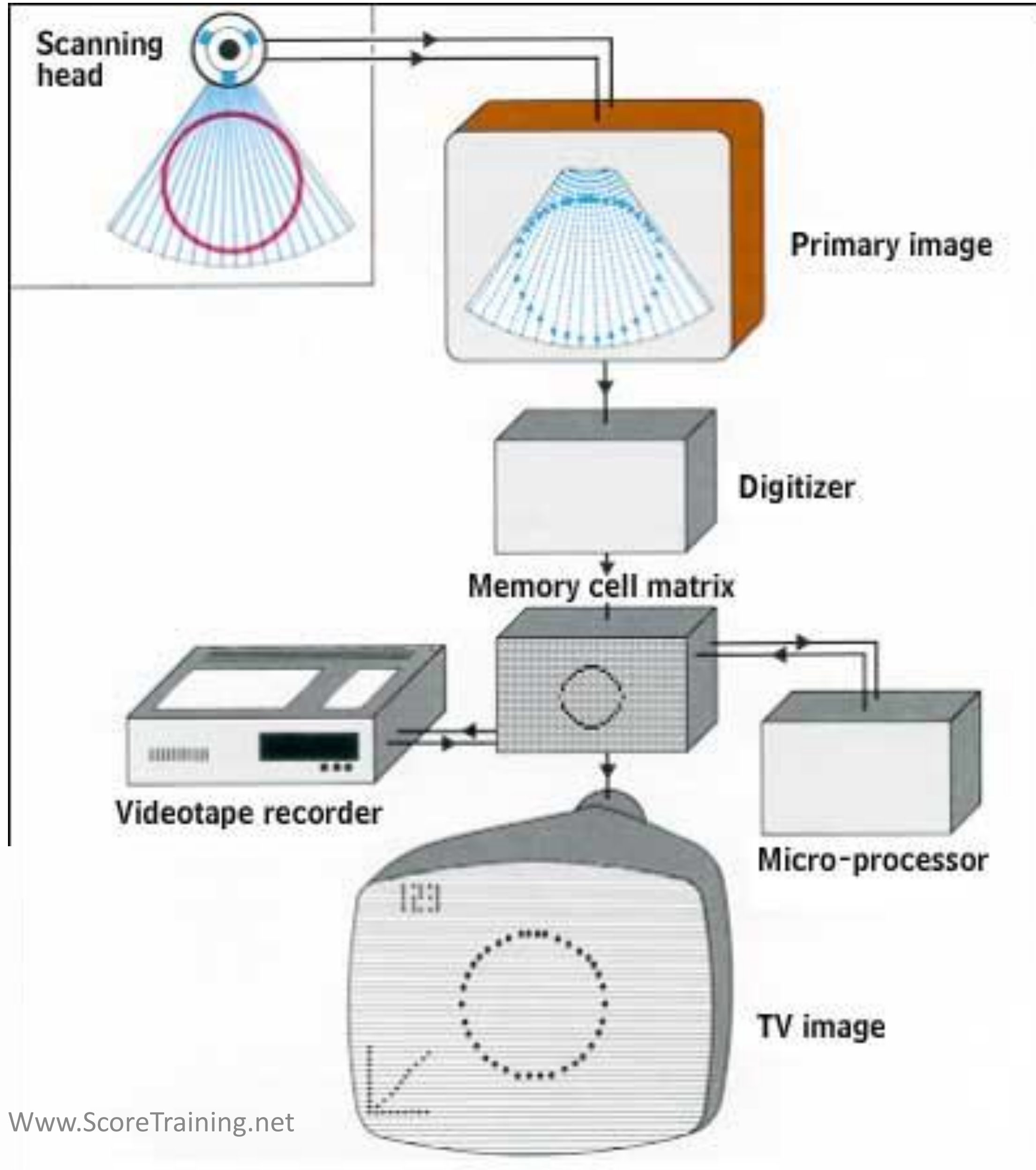
- Real time display of volume images (time varying spatial relationships can be displayed)
- i.e. time is the 4^{th} dimension

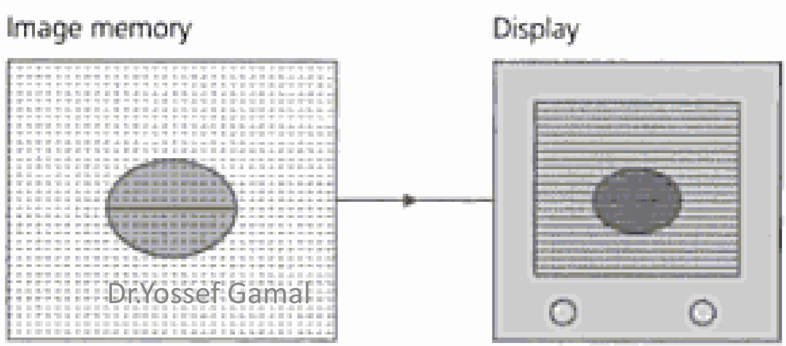
Ultrasound image acquisition

- There are two matrices:

1- matrix in a memory location (each is 6-8 bit memory)

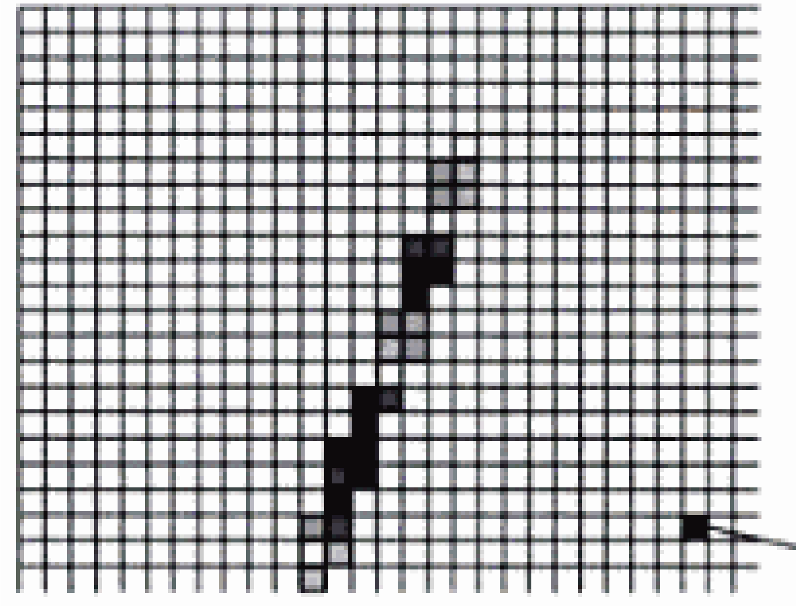
2-matrix on the monitor (gray scale)

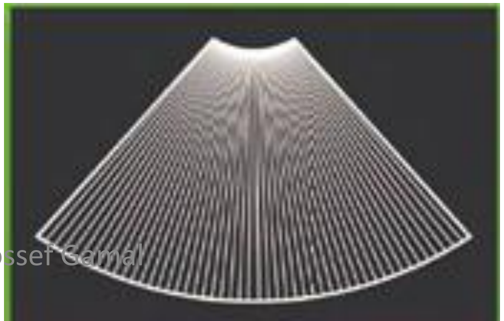


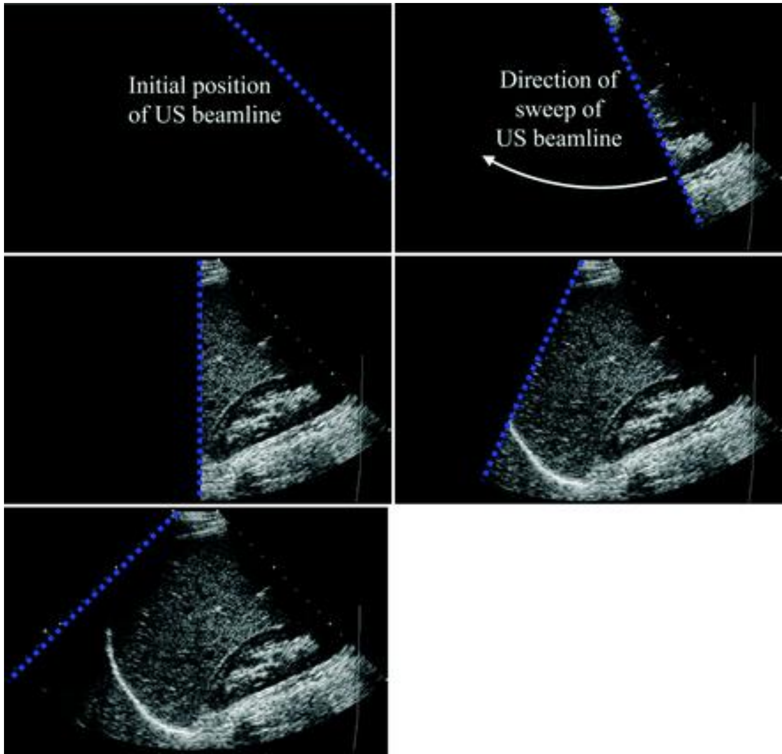


1- write mode:

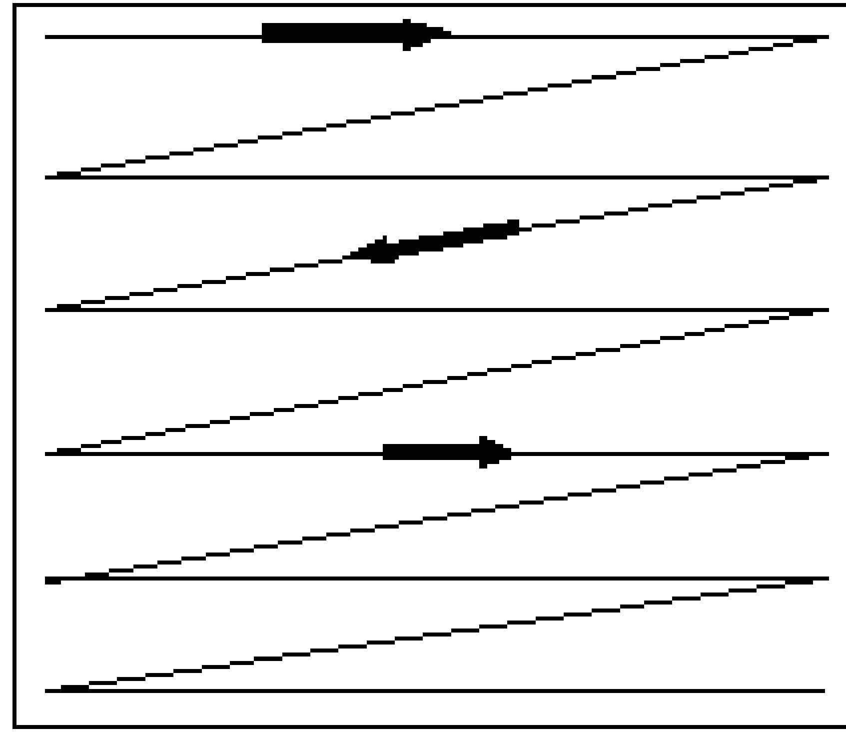
- After Digitalization of echoes they are entered in the memory location matrix in the corresponding scan line of sight
- Each memory location corresponds to the voxel of body section from which echoes arrive
- The figures are continuously updated
- If the pixel is not covered by a scan line , a figure is interpolated from adjacent memory locations (especially at depth)
- Matrix size (512 x 512) is greater than number of scan lines → pixel structure is not noticeable







2-Read mode:



- memory locations are scanned along horizontal lines (as TV monitor scan lines)
- Numbers in memory locations are read out and pass through digital to analogue convertor(DAC)
- Output signal is used to modulate pixel brightness on the monitor screen

i.e. memory locations are written in different order in which they are read (digital scan convertor)

Frame averaging = temporal averaging

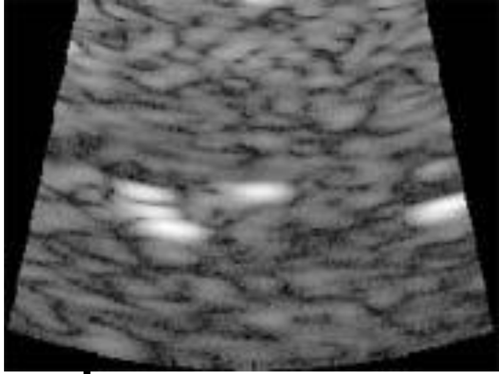
- 5-10 successive echoes from the same point are stored in the same memory location → time average value
- This is performed pixel by pixel over the whole frame
- Advantages: smoothen the picture
- Disadvantage: delay of the frames

Notes:

- image (frame) can be retained in the computer memory while successive scans are carried out and stored as other frames, then , any frame can be selected for display
- Digital scan convertor:
  - Enable freeze frame
  - Enable data manipulation
  - Archive the data

- Image can be stored or hard copied using multi-format camera or laser imager

U/S noise



- Principally electronic noise = statistical fluctuations in the number of electrons in the very small currents measured
- Some additional noise is caused by reverberations in the patient or in the transducer probe
- Minimum signal that can be detected is just greater than the noise

Dynamic range of signals

- Definition: ratio of maximum signal to minimum signal that can be detected

$= 1:10^7$ or $1:10^8$ = 70 -80 dB

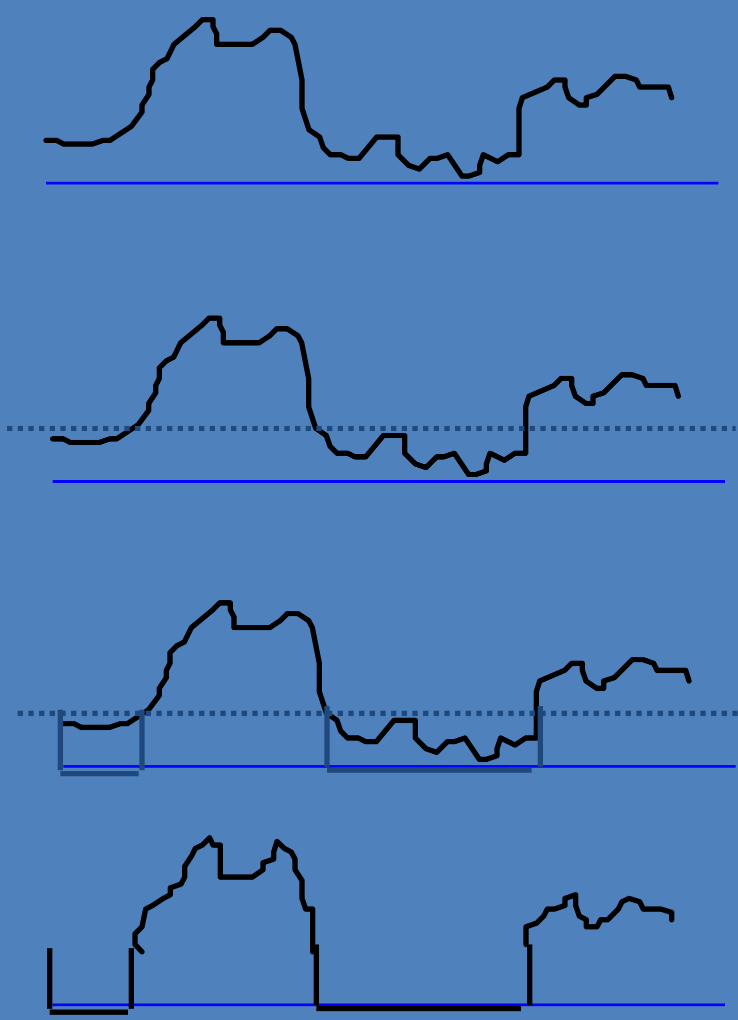
- After TGC (which increase the minimum value) dynamic range will be 40-50 dB

Dynamic range compression:

- Dynamic range is compressed from 40-50 dB to 20-30 dB using logarithmic amplifier
- Cause:
  - Monitor can display brightness range of 25dB
  - dynamic range of the recording film is worse than the monitor
  - The eye can distinguish 30 gray levels only
- This means that the computer memory pixels must be able to store 8 bit depth = 256 different echo levels = 24dB dynamic range

Image processing

- Edge enhancement:
  - increase signal changes at the interfaces
- Reject control:
  - eliminate low amplitude noise and scatter (filtering)
  - Sometimes noise will exceed threshold level and is included in the image

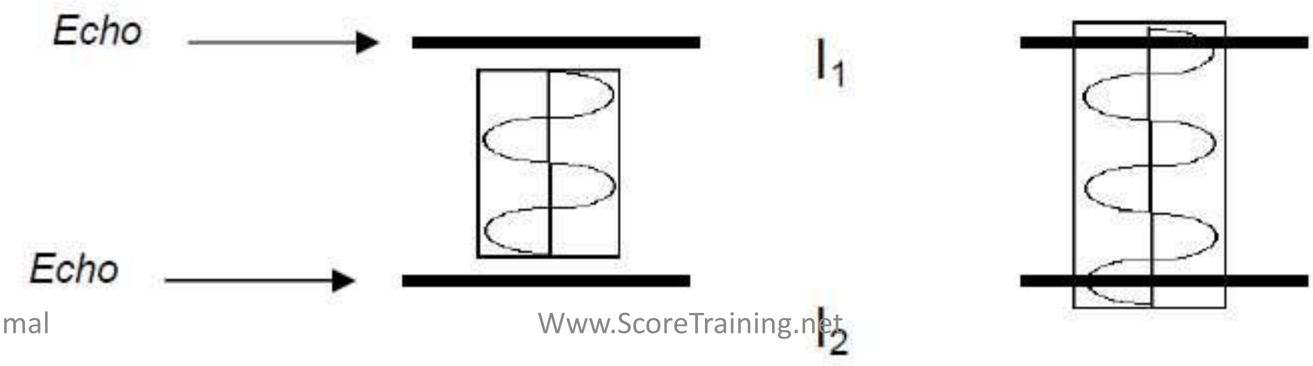


Amplitudes below dotted line reset to zero

Ultrasound resolution

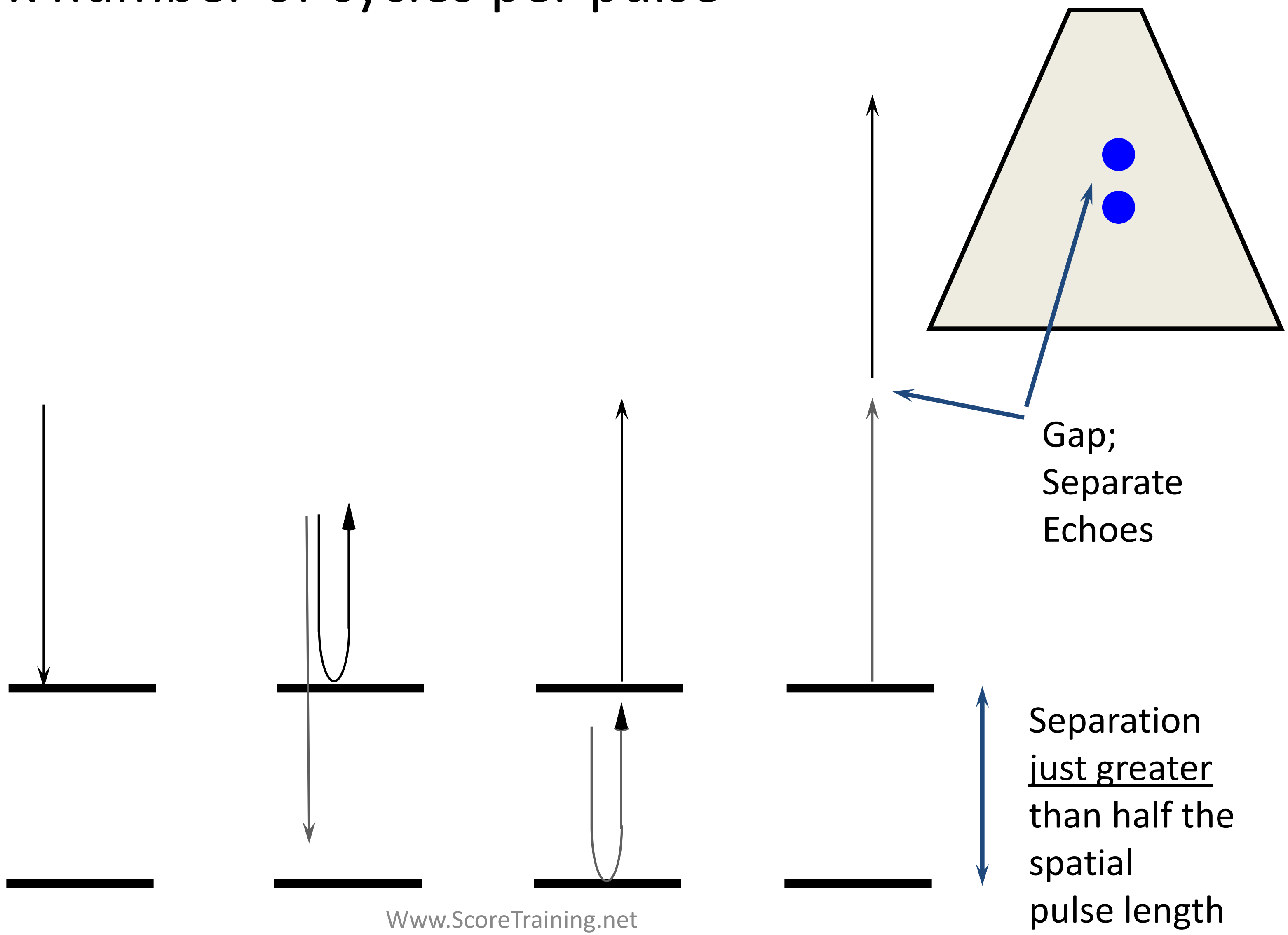
Axial resolution

- The ability to separate two interfaces along the same scan line
- If two points are so close to each other → they echo pulses overlap and this is recorded as single interface
- Usually less than 1 mm (border < 1mm apart are displayed as one border)



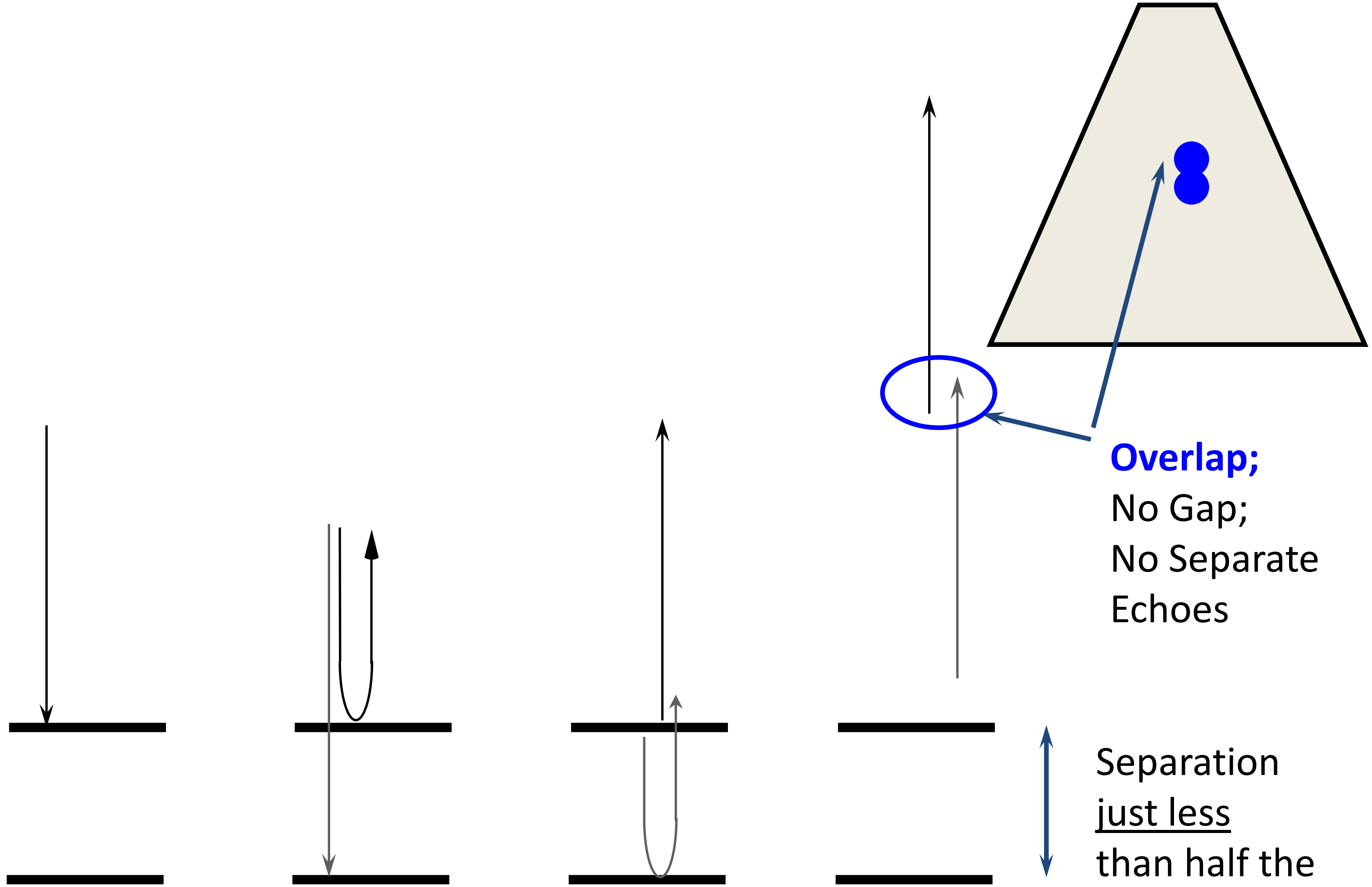
Axial Resolution = Spatial Pulse Length / 2

= ½ λ x number of cycles per pulse



Axial Resolution = Spatial Pulse Length / 2

= ½ λ x number of cycles per pulse



Overlap;
No Gap;
No Separate
Echoes

Separation
<u>just less</u>
than half the
spatial
pulse length

Axial Resolution = Spatial Pulse Length / 2

= ½ λ x number of cycles per pulse

i.e. axial resolution depends on:

A) wave length

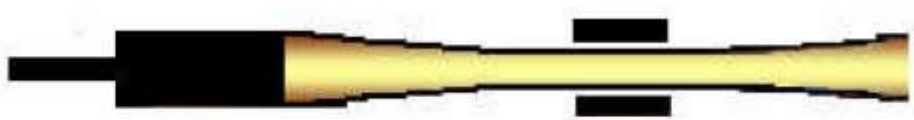
i.e. ↑F →↓ λ→better axial resolution

B) Damping :

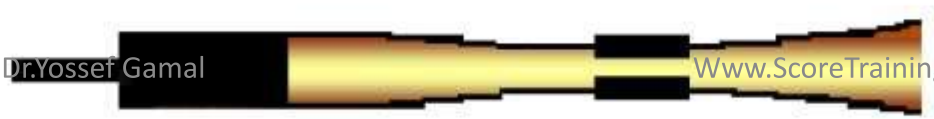
Axial resolution is worsened by ↑ Q (e.g. removing backing block)

Lateral resolution

- Ability to separate structures at the same depth (perpendicular to the beam)
- Beam width must be narrower than the gap between the two structures to be imaged separately
- In case of using non-focused beam: lateral resolution in the near field is highest
- In case of using focused transducer: lateral resolution is the best in the focal region



Objects perpendicular to beam resolved



Objects perpendicular to beam **NOT** resolved

- Formula:

Lateral resolution = effective beam width = beam width in the focal region =

$$\frac{\text{Focal length} \times \lambda}{\text{Diameter of the probe}}$$

i.e.:

- The shorter is the focal length → the narrower is the focal width → the better is the lateral resolution
- The higher the F → the better is the lateral resolution
- The larger is the probe diameter → the better is the lateral resolution

- N.B.

In the focal area :

axial resolution = about one λ

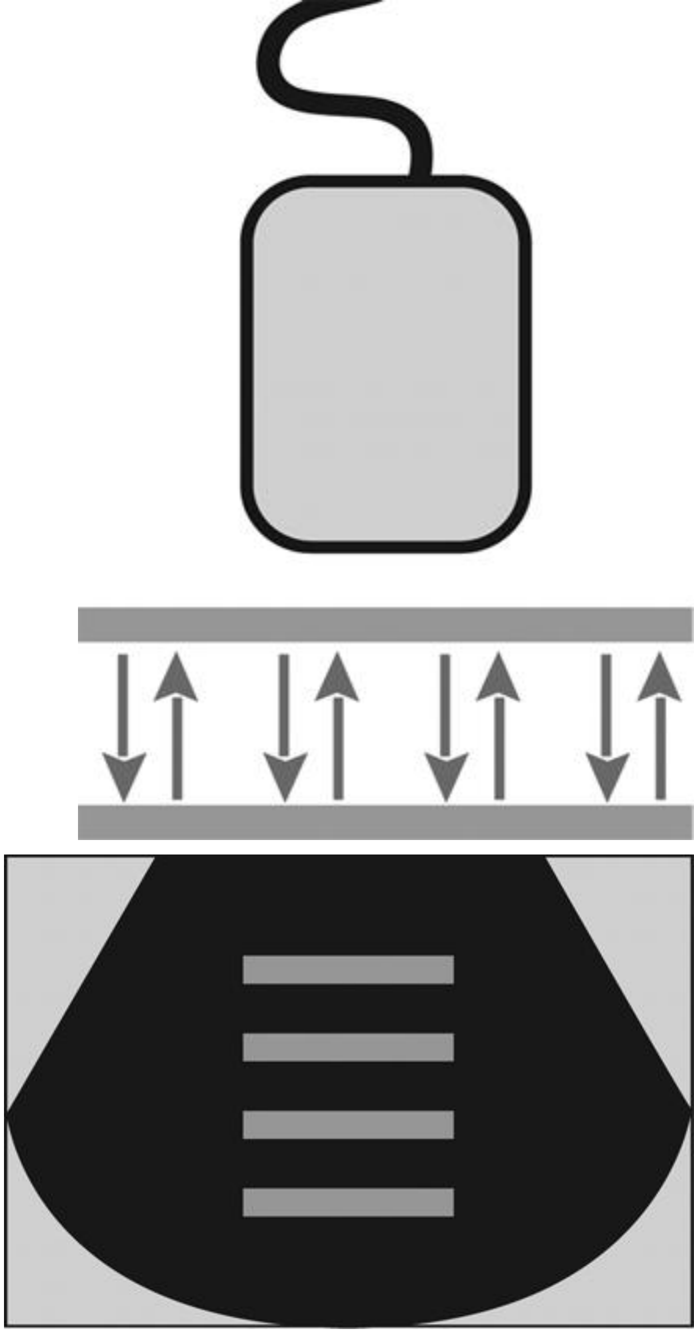
Lateral resolution is 3 times worse

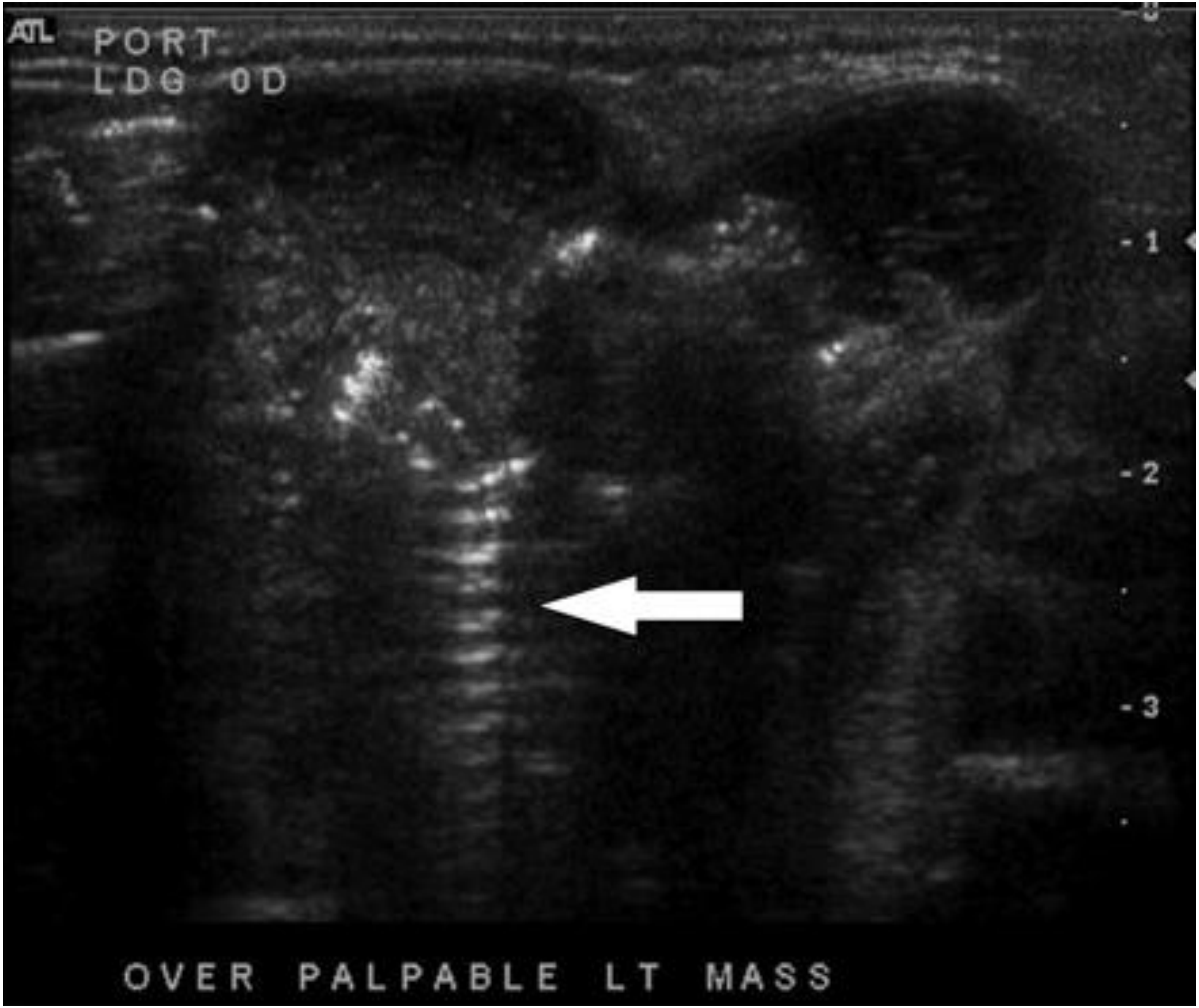
Ultrasound artifacts

Reverberation artifacts

- Multiple reflections to and fro between transducer face and a relatively strong reflecting interface near the surface (or between two body interfaces)
- Produce equally spaced echoes of diminishing amplitude

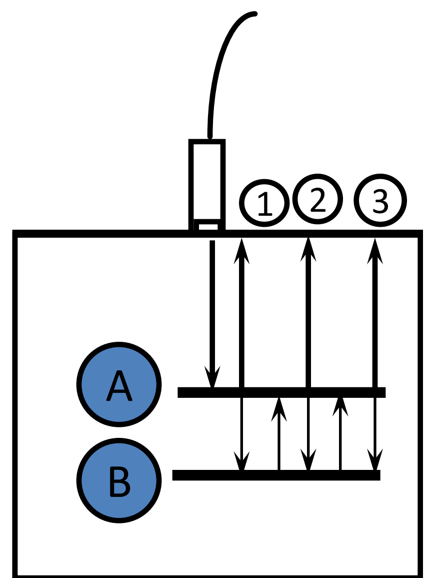
i.e. interface falsely appear to be a distant structure

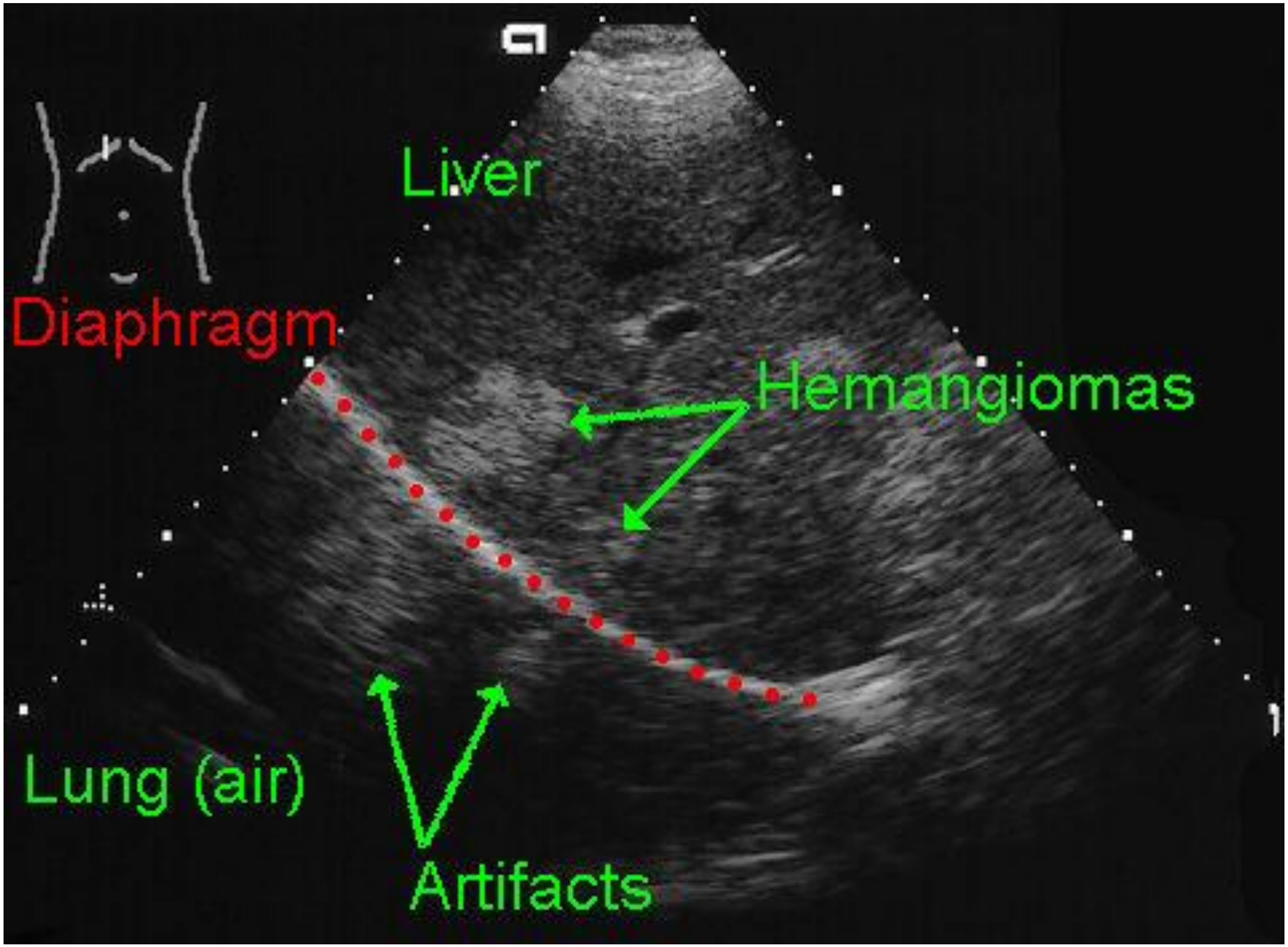



ATL
PORT
LDG 0D
1
2
3
OVER PALPABLE LT MASS

Mirror image (double reflection) artifact

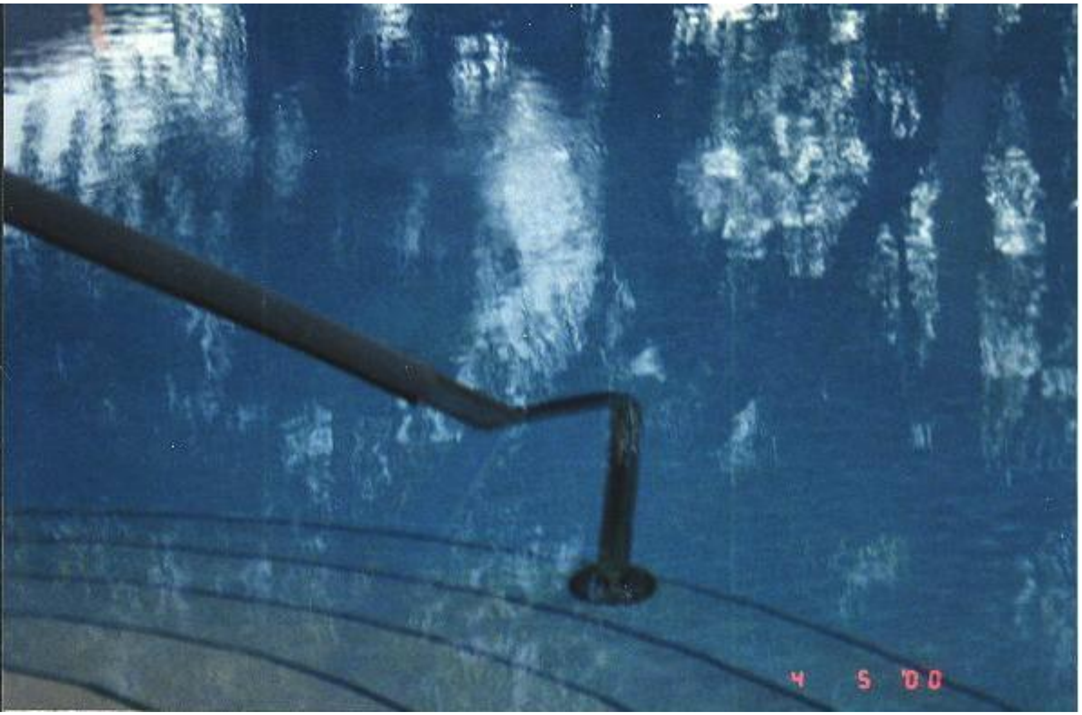
- Multiple reflections between a structure and a strong reflector → creation of a mirror image of the structure beyond the reflector
- Example: diaphragm and liver parenchyma




Liver
Diaphragm
Hemangiomas
Lung (air)
Artifacts

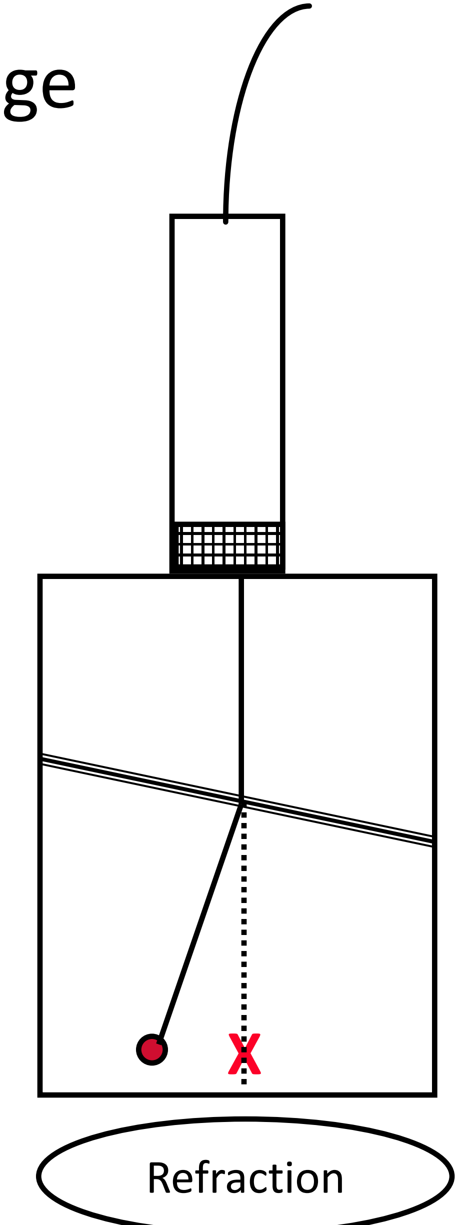
Refraction artifact

- Beam falling obliquely → refraction
- The beam is displaced (and so the image of the structures beyond)



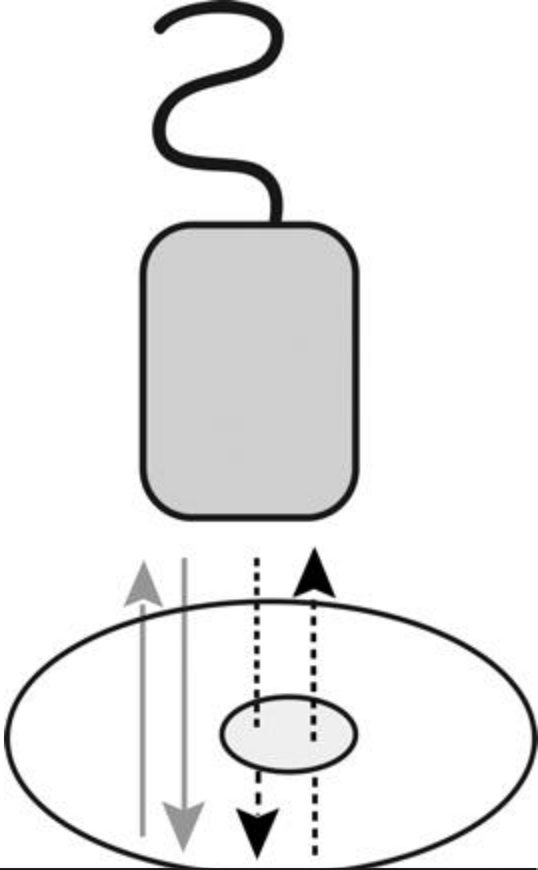
Actual Object Position

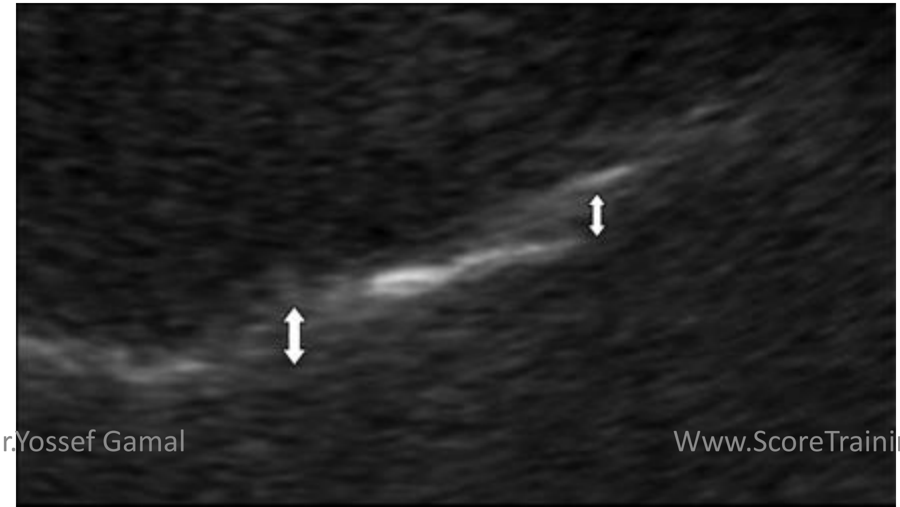
X Position of Object on Image

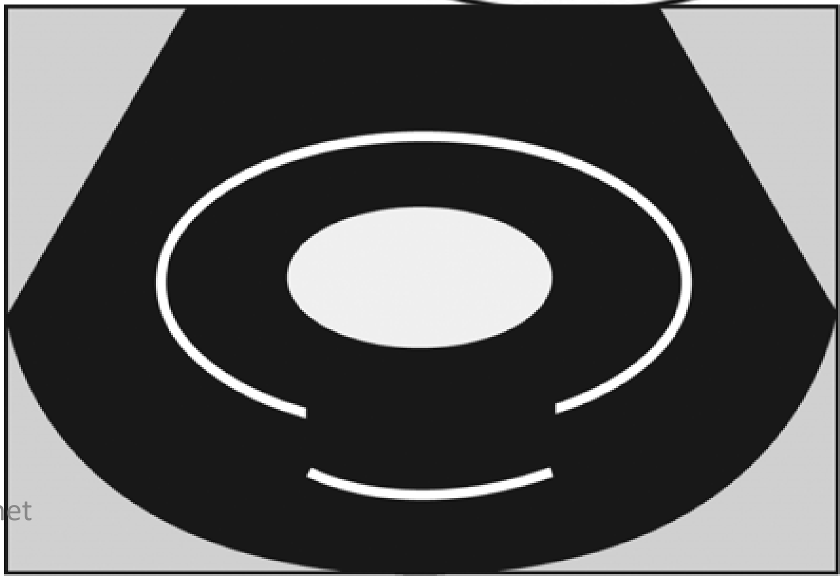


Speed displacement artifact

- In some tissues (e.g. fat) the sound travel slowly
- → the returning echo from distal anatomy is displaced further

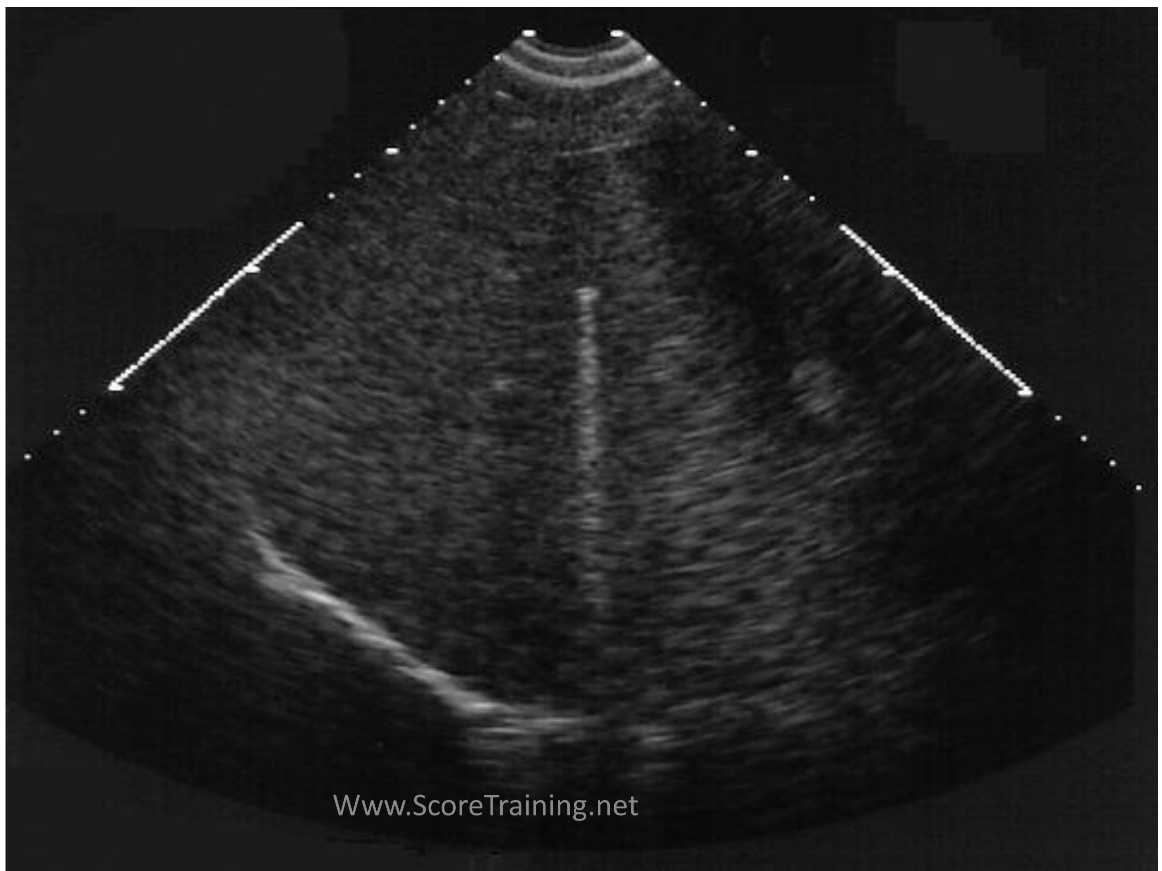






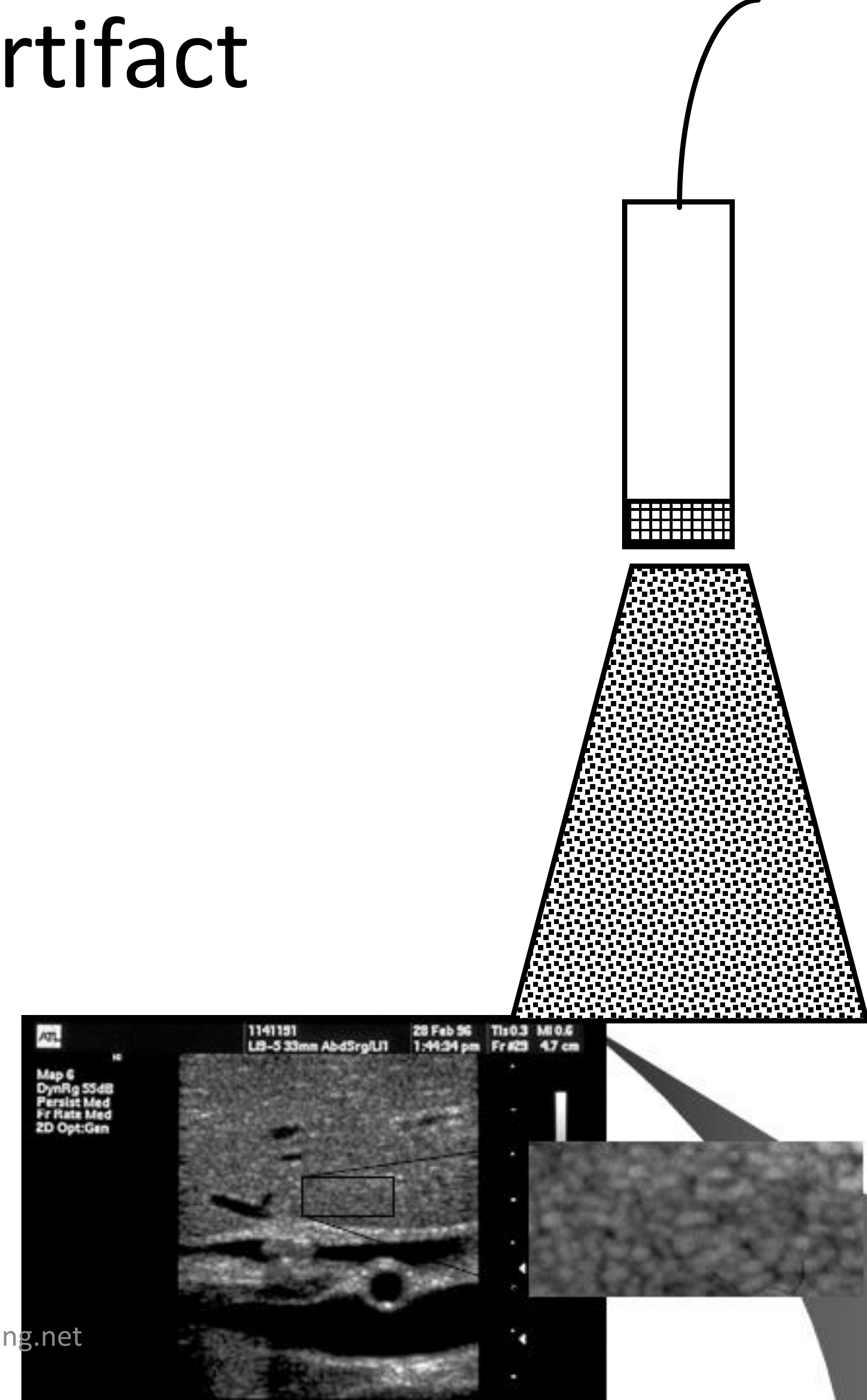
Ring down artifact

- Small concretions or gas bubbles resonate and emit echo continuously → track is seen behind it

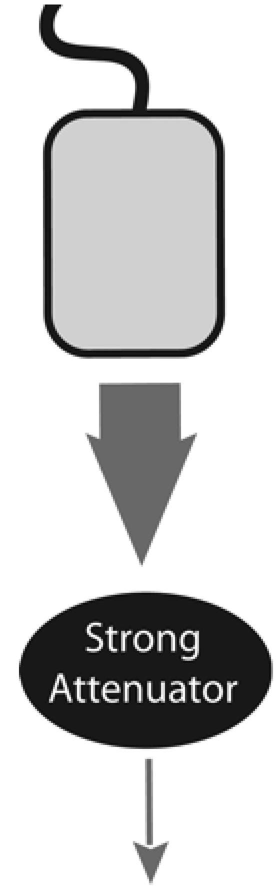


Speckle artifact

- Definition: textured appearance of tissues , e.g. liver
- Cause: structures which are too small and close to be resolved
- Result: scattering of the sound waves , which interfere with each other → echo pattern is random and unrelated to the actual pattern of scatterers within the organ

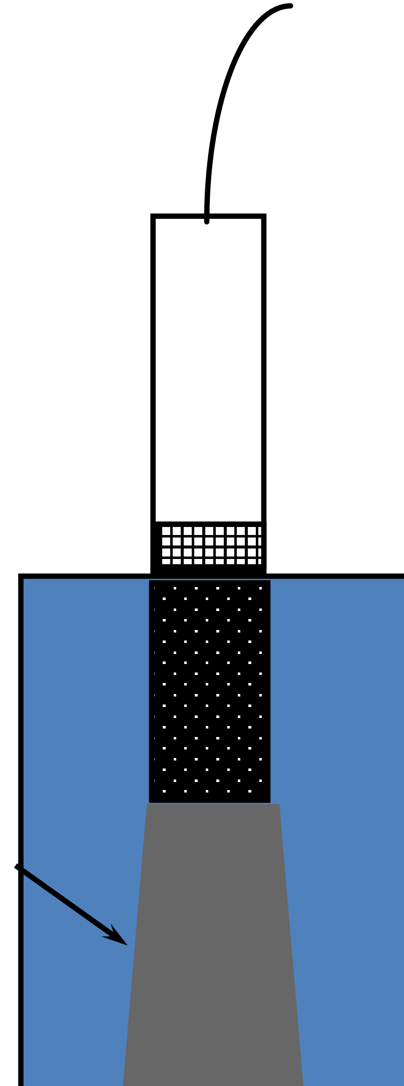


Acoustic shadowing



- Cause: strongly attenuating (bone , gall stones) OR reflecting (bowel gases , lung) structures
- Result: reduction of the intensity of echoes from the region behind them → shadowing

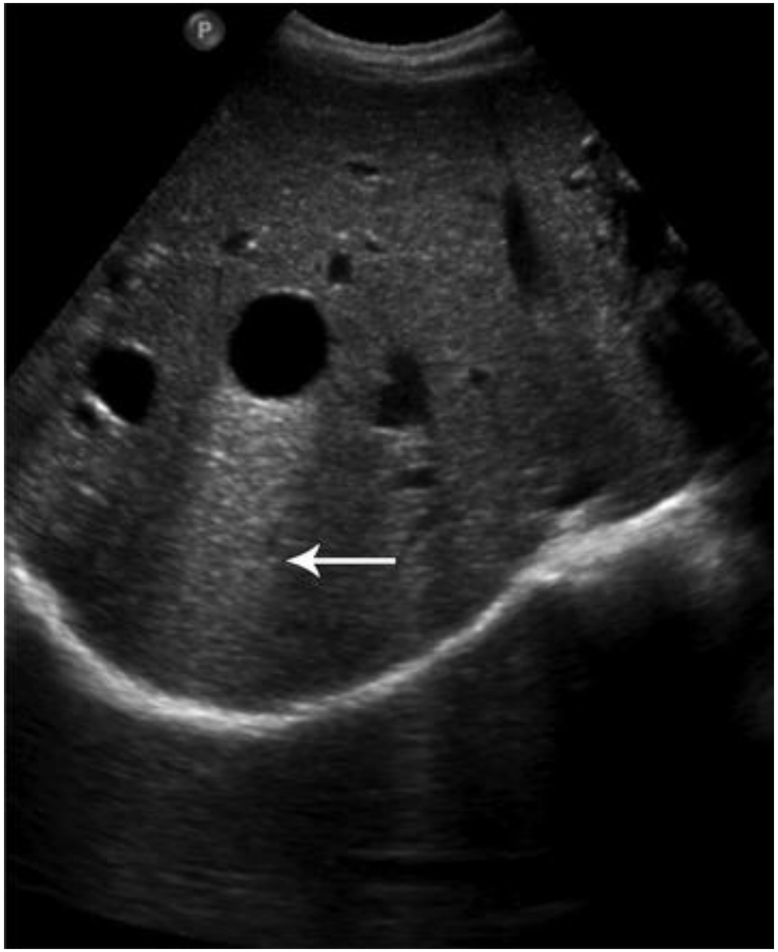

Gallstone
GB
.0
.5
1.0
1.5
2.0
2.5
CINELOOP (TM)
FEATURE

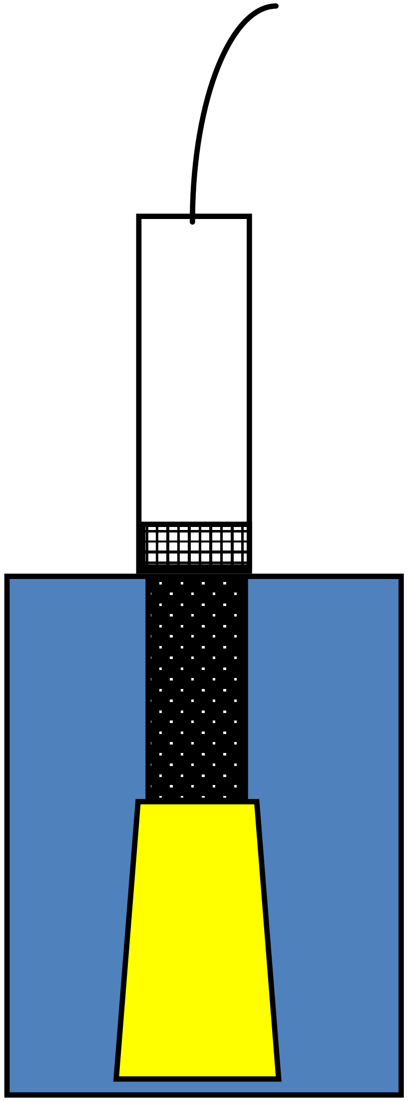

Shadowed
Reflector

Acoustic enhancement

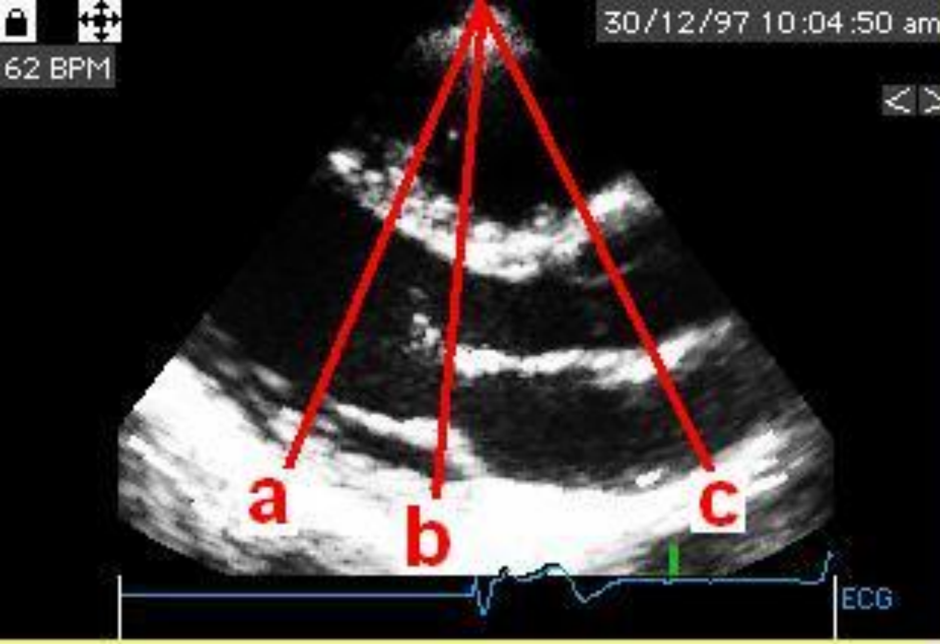
- Cause: fluid filled structures (e.g. UB, cyst) which are weak attenuators of the U/S beam
- Result: relative increase in the intensity of echoes from the tissues behind them (negative shadow)
- N.B: acoustic shadowing and enhancement are made worse by TGC

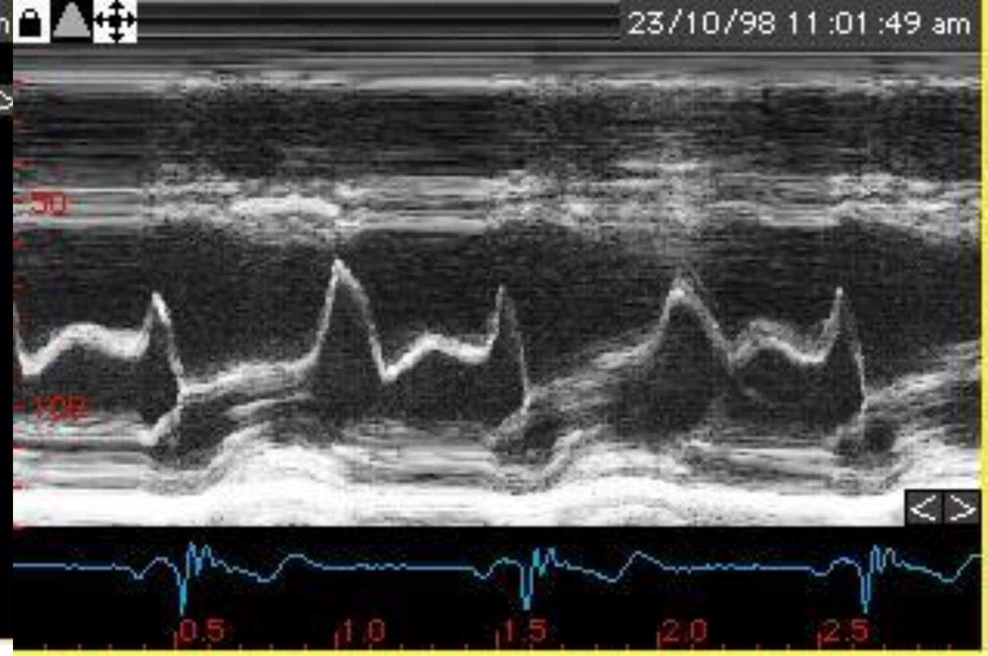
Enhancement

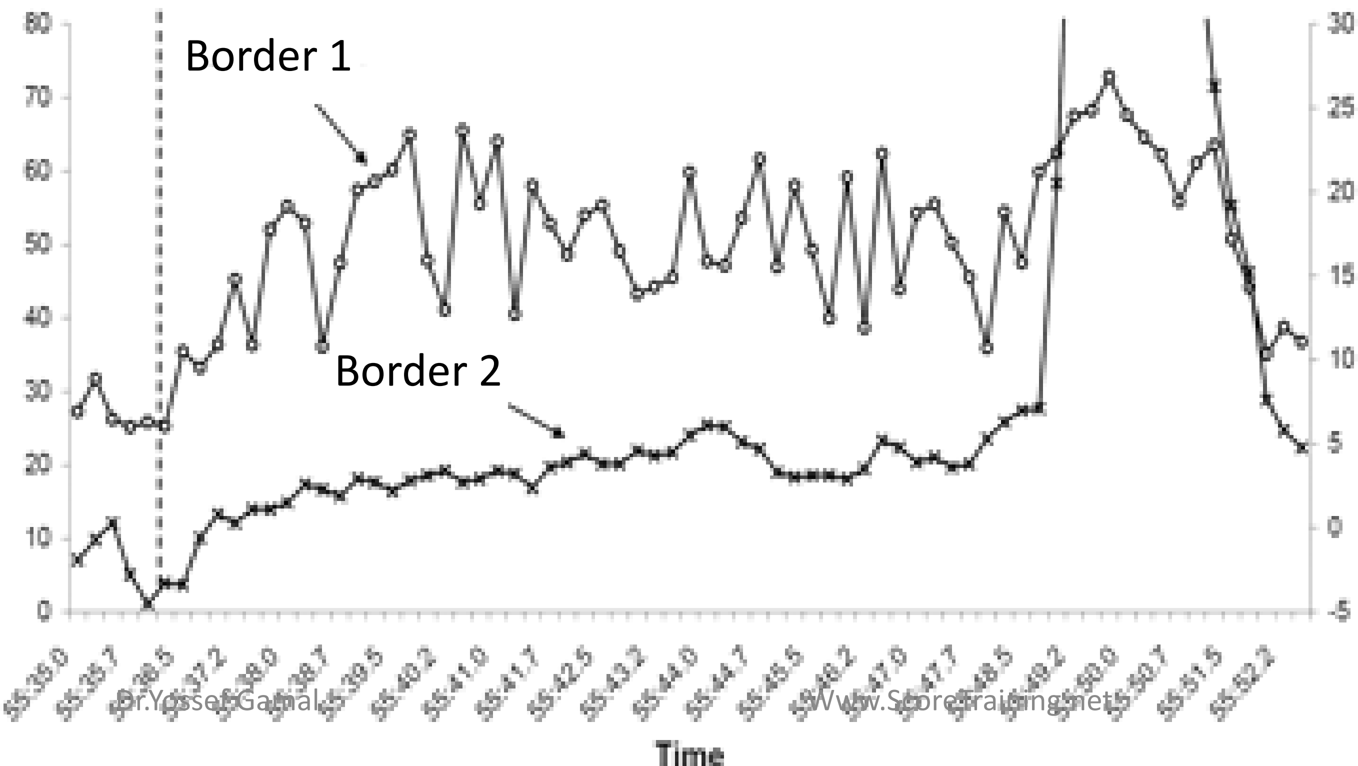


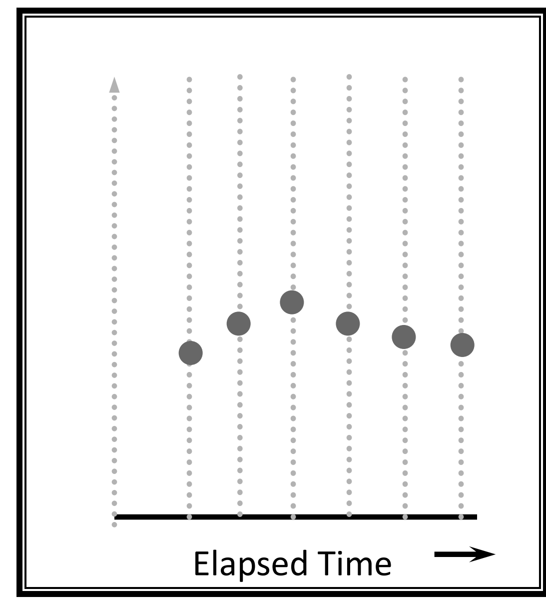


M-Mode (<u>M</u>otion mode) ultrasound



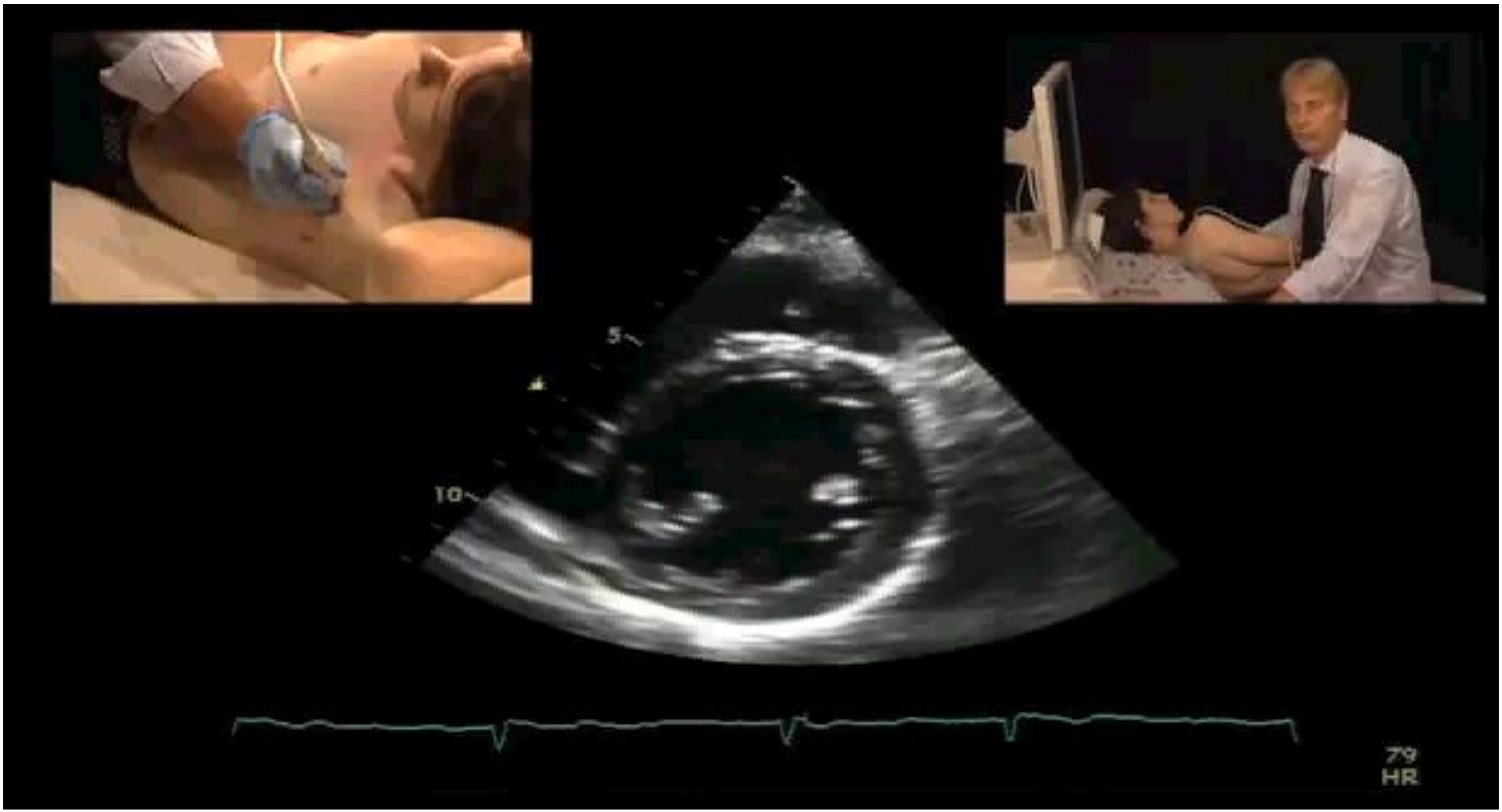




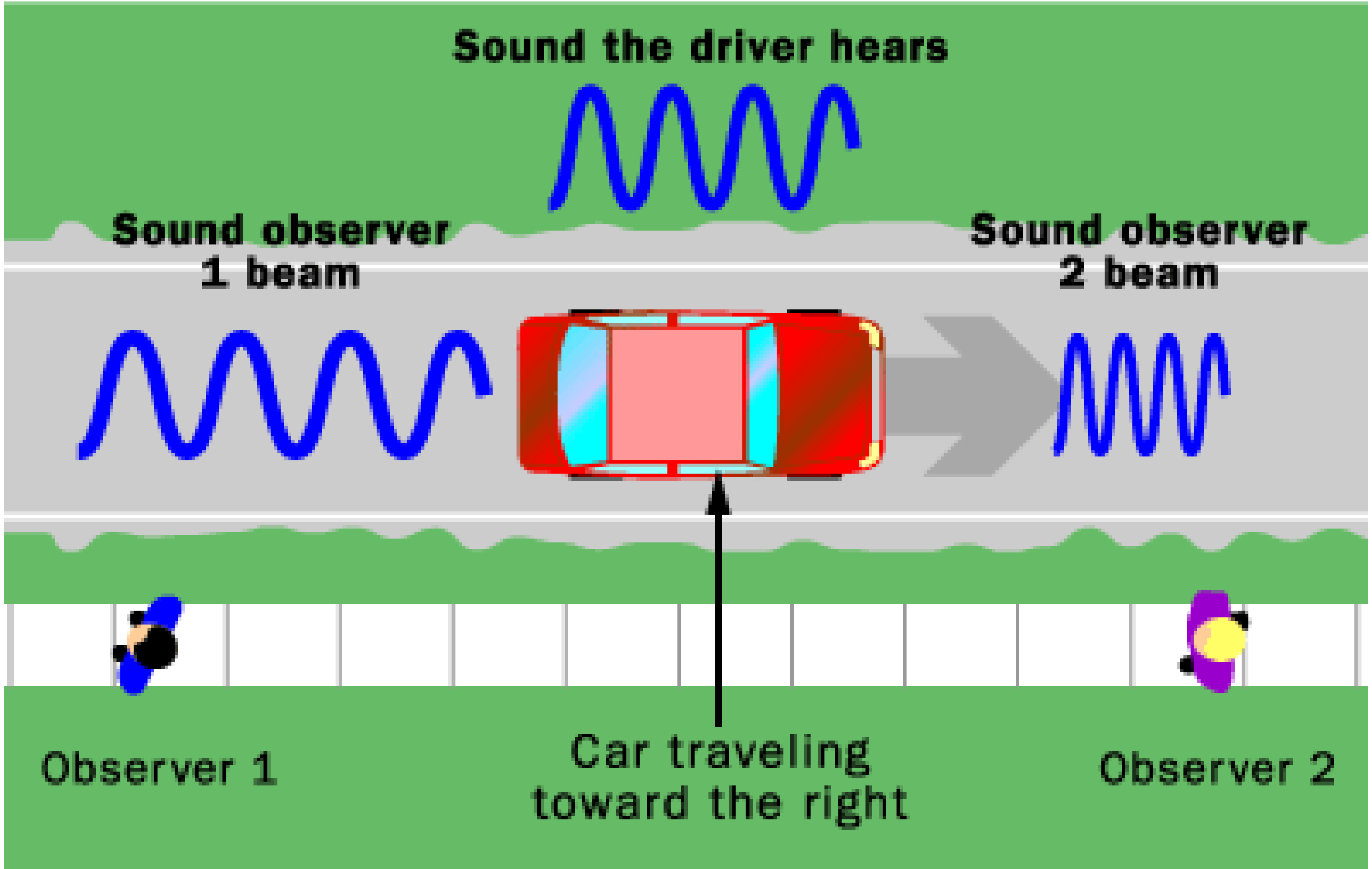


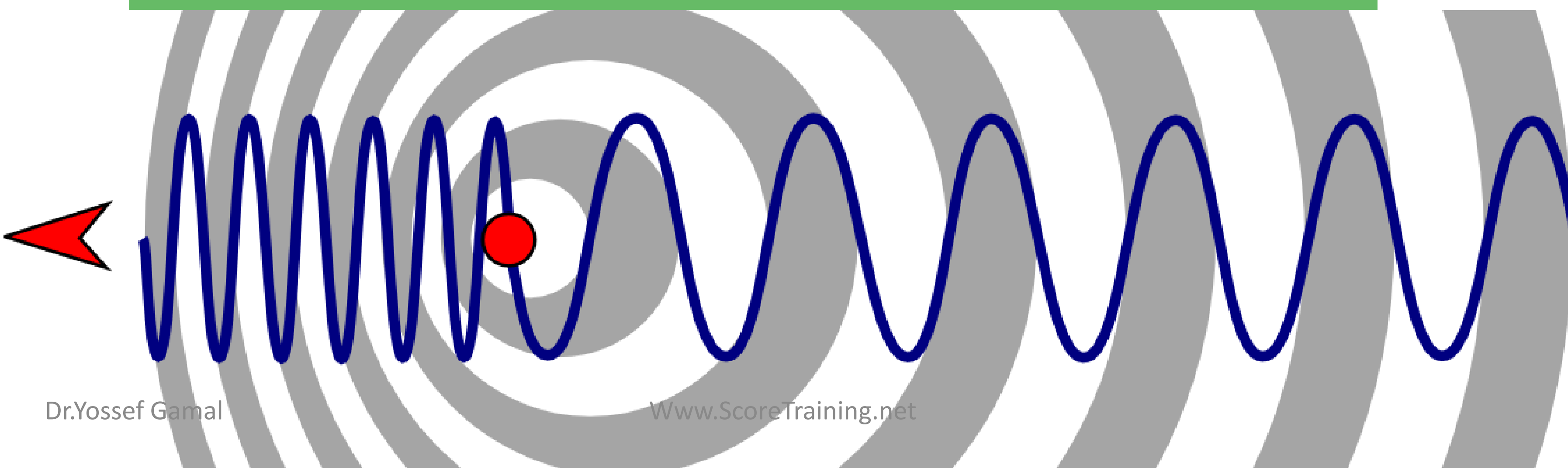
Each vertical line is one pulse

- **Uses:**
  - imaging of cardiac walls and valves
- **Process:**
  - B-mode image is frozen on the screen,
  - This image is used to direct the beam from the stationary transducer along a line of interest
  - This line intersect the moving surfaces of the heart as nearly as possible at right angles
  - Echoes are displayed on the screen as a line of moving bright dots against time
- **Advantages:**
  - Better than B mode for imaging of the heart (which moves too quickly to be followed by normal B mode)
  - Quantitative analysis is possible (e.g. timing of flow across a valve)


5
10
79
HR

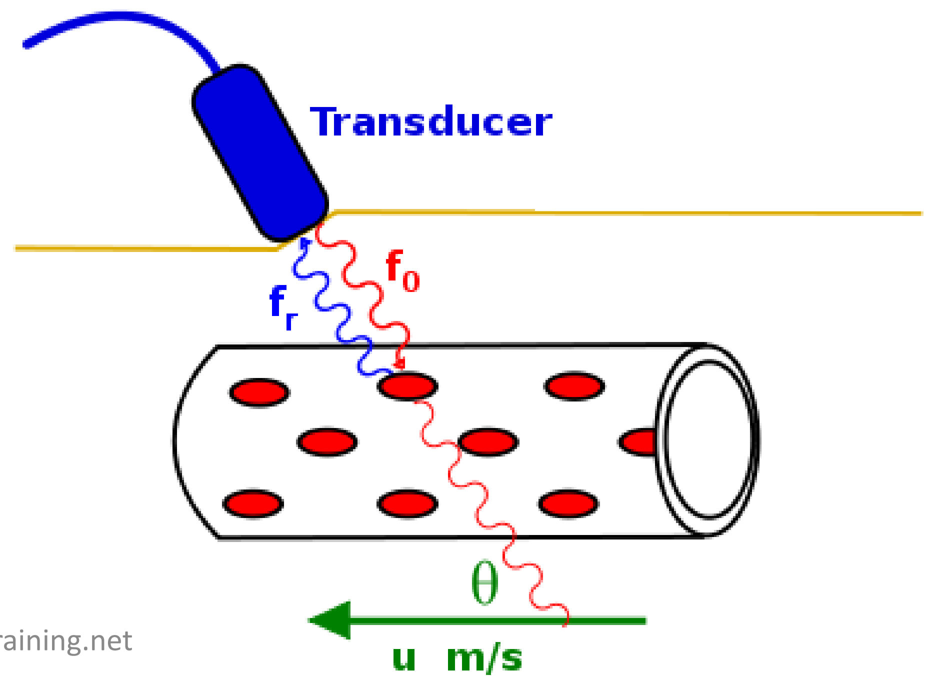
Doppler ultrasound


Sound the driver hears
Sound observer 1 beam
Sound observer 2 beam
Observer 1
Car traveling toward the right
Observer 2

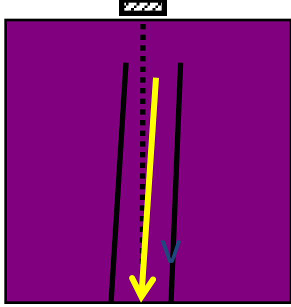


Doppler effect

- When incident sound waves are reflected by moving interface that is approaching the transducer , the wave is compressed
  - i.e. λ is reduced and so Frequency is increased (velocity constant..why?)
- With receding reflector , the opposite occur , and frequency is reduced
- The change in frequency is called Doppler shift



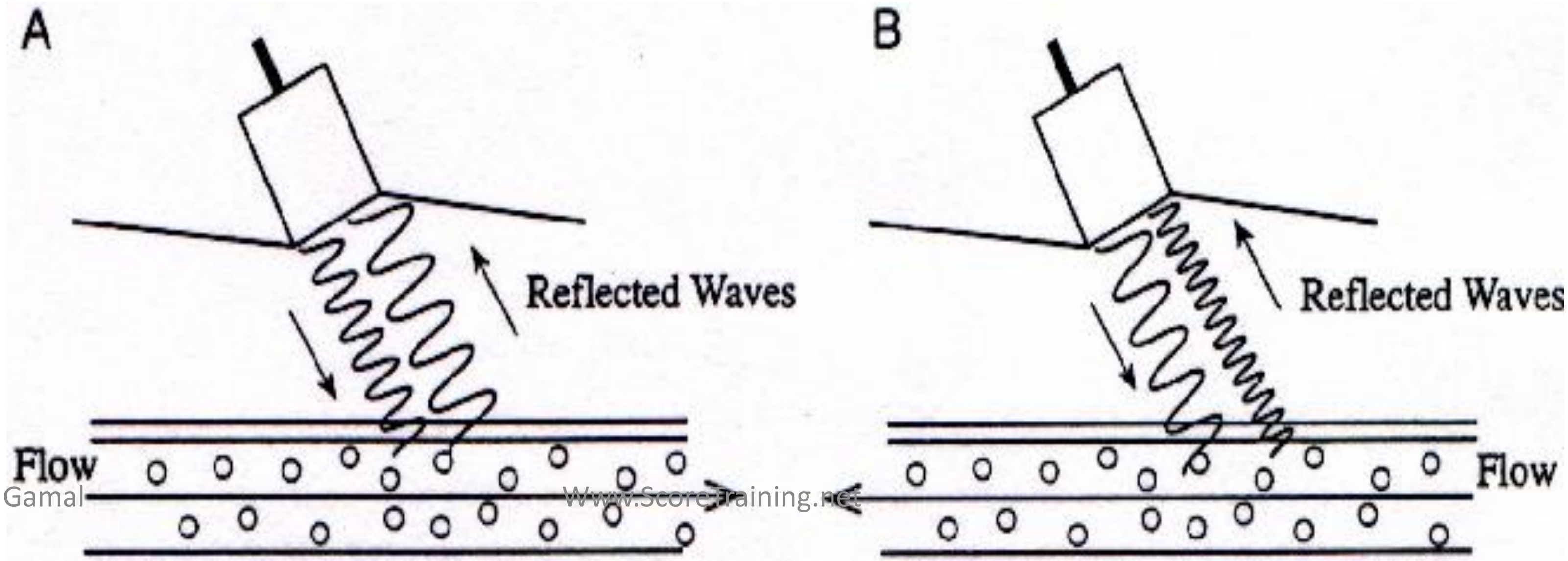
$$f_D = f_r - f_o = \frac{2 \times f_o \times v}{c}$$



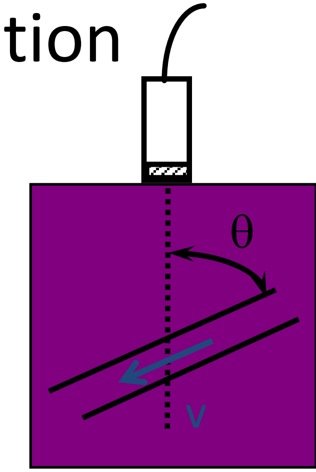
f_D =Doppler Shift in MHz
f_e = received frequency (MHz)
f_o = original frequency (MHz)
v = reflector speed (m/s)
c = speed of sound in soft tissue (m/s)

i.e. The change of frequency (Doppler shift) is proportional to the velocity of the interface, and the transducer frequency

N.B. This assumes that the motion is in the same direction of sound waves



Effect of changing the angle of the reflector motion (angle of insonation)

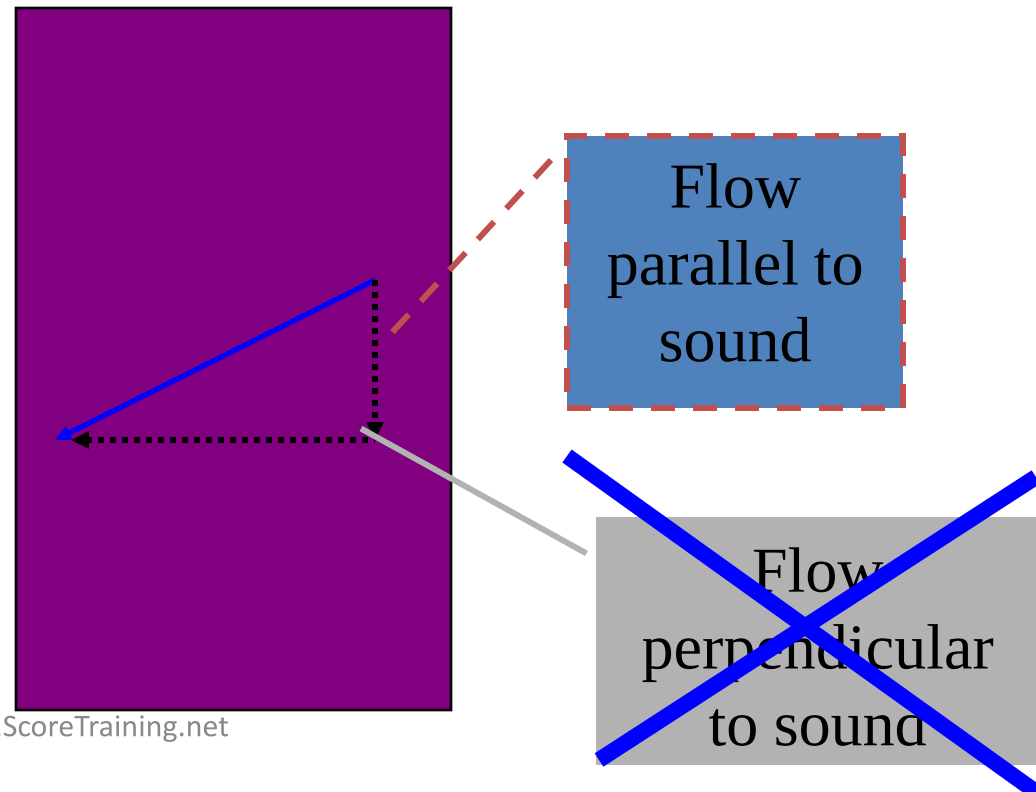


$$f_D = f_e - f_o = \frac{2 \text{ X } f_o \text{ X } v \text{ X } \cos\theta}{c}$$

i.e.

When $\theta = 90^o \rightarrow$ doppler shift = 0 (compare to B-imaging)

When $\theta = 0^o \rightarrow$ doppler shift is at maximum value



$$f_D = f_e - f_o = \frac{2 \times f_o \times v \times \cos\theta}{c}$$

Notes:

- Doppler shift is in the audible frequencies range (0 – 10 KHz)
- By measuring the received frequency , scanner can calculate the change of frequency occurred (doppler shift) , and so the velocity of the reflector
- The direction of the movement can be known by determining whether the frequency was increased or decreased

N.B.

- doppler pulses are the same as B-mode pulses in all aspects and parameters
- With short doppler pulses (↓Q): it is not possible to get accurate flow information (why?)
- With long pulses (↑Q) it is not possible to distinguish vessel depth accurately (why?)


Thank you